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Green finance & carbon neutrality: strategies and policies for a sustainable future

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Green finance & carbon neutrality: strategies and policies for a sustainable future

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Editorial: Green finance & carbon neutrality: strategies and policies for a sustainable future

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KEYWORDS

green finance, carbon neutrality, technological innovation, carbon trading mechanisms, environmental benefits

Editorial on the Research Topic
Green finance & carbon neutrality: strategies and policies for a sustainable future

Introduction

Facing severe global environmental challenges, nations must prioritize carbon neutrality. In this context, green finance is key for sustainable development and environmental protection, and is attracting increasing attention. This Research Topic, "Green Finance & Carbon Neutrality: Strategies and Policies for a Sustainable Future", includes 35 studies highlighting green finance's role in transitioning to a low-carbon economy. Articles analyze green finance strategies in various economies and industries, discussing policymaking to support sustainable growth and environmental improvement. With interdisciplinary approaches and innovations, this Research Topic aids policymakers, researchers, and practitioners in tackling green transition challenges, offering insights for achieving global sustainability.

Green finance and technological innovation

Green finance and technological innovation reshape the global economy as key carbon neutrality drivers. They support sustainable investments and balance growth with environmental protection, offering pathways for a sustainable future.

In *Measurement, Dynamic Evolution and Pollution Emission Effects of the Coupling of Green Finance and Digital Technology - Evidence from China*, Liu et al. investigate the interplay between green finance and digital technology in China using a game theory-based weighting method. Results show increasing provincial coordination, club convergence, and a "Matthew Effect" (where advantaged regions gain more). This synergy promotes pollution reduction through green innovation, offering critical support for synergistic interactions.

Zhang et al. demonstrated that digital financial inclusion boosts sustainable agriculture in China by offering accessible, low-cost services. The study, covering 31 provinces

(2013–2021), revealed impacts via industrial structure and entrepreneurship, with spatial spillover effects, highlighting its transformative potential for policy and practice.

Liu and Zhu explore how green finance influences carbon emission intensity and efficiency, highlighting the digital economy as a moderator. Findings show green finance reduces emission intensity via mechanisms like green innovation and enhances emission efficiency. The digital economy amplifies these effects, supporting policies for green finance and environmental protection.

Low-carbon policies and urban development

Low-carbon policies are vital for urban development, reducing emissions, fostering sustainable growth, and improving life quality. Green finance supports this transition, funding clean energy, green infrastructure, and ecological innovation.

Geng and Yang examine low-carbon economy pilot policies' effects on economic development and urban ecological efficiency. Their findings show a 2.2% increase in ecological efficiency in pilot cities. While industrial structure optimization was negligible, energy structure improvements were notable. The research validates these policies as effective in advancing green urban development.

Xiao et al. show that the low-carbon city pilot policy boosts urban circular economies by 6.42%. An analysis of 273 Chinese cities (2012–2022) reveals industrial structure rationalization as a key mediator. Expanding this policy can further support sustainable economic transitions.

Li et al. show that green finance and new infrastructure significantly improve carbon emission performance in Chinese cities, especially in marketized eastern regions, policy-supported digital sectors, and resource-based cities. Key pathways include green innovation, industrial upgrading, and resource optimization.

Carbon trading and market mechanisms

In global climate change efforts, carbon trading is key for carbon neutrality. By trading emission rights, it encourages emission reduction, tech innovation, and sustainable investment. Analyzing these markets enhances policies, benefits the environment, and transforms economies.

Han et al.use a Time-Varying Parameter Vector Autoregression- Bayesian Kalman Model (TVP-VAR-BK) model to study risk spillover between China's carbon market and high-emission industries. The carbon market's short-term impact is greater on the cement industry, while long-term effects stem from industry fluctuations. Economic policy uncertainty significantly influences risk spillovers asymmetrically at the median but not at extreme quantiles, indicating a complex transmission mechanism.

Tian et al. demonstrate that China's Carbon Emission Trading (CET) significantly boosts the construction industry's green development. Analysis of 107 listed companies (2007–2022) shows a 0.36 GTFP increase. The Difference-in-Differences method reveals CET's impact, particularly on large, state-owned, indebted companies, and those in the east receiving subsidies. Future research should explore CET effects across sectors and regions.

Han et al. show that carbon trading policies significantly lower corporate carbon emission intensity across ownership types, marketization levels, and digitalization. Using 2009–2019 A-shares data, they reveal that these policies drive nearby firms to cut emissions via demonstration and competition. Initially, ESG information disclosure weakens this effect but later enhances it as ESG ratings improve policy efficacy. This study guides policy optimization towards "dual carbon" goals.

Corporate environmental performance and financial impact

Amid serious global ecological challenges, corporate environmental performance increasingly affects financial markets. Green finance prompts corporate upgrades and influences financial outcomes and investor choices. Studying this relationship aids understanding of green finance, aiding policymakers and resource allocation for a low-carbon economy.

Zhu et al. show the "Green Credit Guidelines" policy enhances corporate environmental investments. Using A-share data (2004–2020) and PSM-DID, the study finds variable impacts based on ownership and region. Green credit increases financing constraints, encouraging environmental investment, innovation, and capital structure change. Macroeconomic and monetary policies, alongside government focus, affect investment attitudes, informing green finance policy-making.

Zhang et al. reveal that ESG performance boosts technological innovation in China's A-share companies. From 2011–2021, ESG enhances innovation through better network positions, increased institutional ownership, reduced labor costs, and eased financing constraints. Effects are stronger in labor-intensive, private, competitive, mature firms. Companies should enhance ESG practices, communication, and equity structure, while governments should improve ESG policies.

Guo et al. show green finance in China (2004–2021) significantly reduces carbon emissions, with green credit being most effective. Regional variances exist. Command-control tools aid reduction; market tools are less effective. This informs precise policies and promotes regional cooperation for climate goals.

Environmental policy and social impact

Effective environmental policies profoundly impact ecosystems, transform social structures, and lifestyles. They enable rational resource allocation, promote a green economy, and enhance public awareness. This harmony fosters sustainable economic, social, and environmental development.

Jing and Feng used a "Tool-Goal-Object" framework to analyze "dual carbon" policy texts. They identified tool imbalance, limited target coverage, object misalignment, and poor dimensional compatibility. Their suggested improvements aim to optimize the policy framework for better environmental outcomes.

Dempere et al. highlight greenwashing tactics in sustainable finance, such as vague terms and information opacity, harming reputation and trust. They stress stronger regulations and true transparency to mitigate risks, despite weak current measures.

Jiang et al. used a set-theoretic approach to study China's environmental policy implementation complexity. They found four configurations: "priority governance" for high pollution, "financial emphasis" in the northwest, "coordinated implementation" with socio-economic conditions, and a "comprehensive strategy" in capitals. These insights aid regional policy optimization.

Economic development and environmental benefits

Balancing economic growth with environmental benefits is urgent. Green finance bridges this gap, facilitating carbon neutrality through efficient resources and innovation. Sustainable development demands integrated policies, market mechanisms, collective action, and long-term commitment.

Wen et al.found that RCEP bilateral trade enhances economic growth and reduces pollution in ASEAN countries, though carbon mitigation is uncertain. Differences exist between ASEAN and non-ASEAN regions. The study suggests optimizing environmental quality to support growth and transition.

Zhang et al. find that financial inclusion, urbanization, and energy efficiency improvements significantly enhance environmental performance for "Belt and Road" countries. Additionally, green finance can drive low-carbon innovation in China's aging economy, promoting market diversity and balancing economic and environmental goals.

Rizwanullah et al. analyzed factors influencing Belt and Roads Initiatives (BRI) countries' environmental performance using 1991–2021 data. Financial inclusion, urbanization, trade, and industry impact ecology. Findings stress robust policies for sustainable economic and environmental progress.

Conclusion and future directions

The 35 articles in this Research Topic comprehensively examine the crucial role of green finance in promoting the transition to a low-carbon economy. The research addresses the implementation of green finance strategies across different economies and industries, as well as how policy formulation can effectively support these efforts to foster sustainable economic growth and environmental enhancement. As the global community continues to confront the challenges posed by climate change, these studies underscore the importance of interdisciplinary approaches and cross-sector collaboration. By integrating technological innovation, financial mechanisms, and public participation, relevant stakeholders can make significant progress toward achieving a low-carbon and sustainable future. Future research should further explore the synergistic effects of green finance and digital technologies, deepen the effectiveness of policy support, and expand cross-regional collaboration to advance the realization of global sustainable development.

Author contributions

XL: Conceptualization, Writing–original draft, Writing–review and editing. WZ: Investigation, Writing–original draft, Writing–review and editing. ML: Investigation, Writing–review and editing. JH: Investigation, Writing–review and editing.

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How fintech affects financial sustainability in the electric power industry?—evidence from Chinese companies

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Introduction: The financial sustainability of the electric power industries is of significant practical significance for achieving carbon neutrality and peak carbon emissions.

Methods: We innovatively use web crawler technology to obtain keywords related to fintech in the search index and constructs a regional fintech indicator system. Based on this indicator system, we explore the impact of fintech on the financial sustainability of the electric power industry by panel regression model. The result shows that fintech significantly improved the financial sustainability of electric power companies. Further evidence indicates that fintech can promote financial sustainable development by enhancing corporate risk-taking ability, increasing operating income, and alleviating financing constraints. Heterogeneity analysis indirectly proves that compared to state-owned electric power enterprises, private electric power enterprises face a more severe financing environment. But private enterprises can obtain more credit funds through new financing channels opened by financial technology. So, the role of fintech in alleviating the phenomenon of ownership discrimination in the financial system cannot be ignored. In addition, we also find that fintech is more significant in helping small and medium-sized electric-power enterprises in financial sustainability, while it is less helpful for large enterprises.

Discussion: In the context of the fusion development of technology and financial markets, the research conclusions of this article provide important references for governments, enterprises, and traditional financial institutions to make corresponding reforms.

KEYWORDS

electric power industry, fintech, financial sustainability, financing environment, China

1 Introduction

The current global economic situation is severe, with increasing risks and challenges, various industries face some unknown encounter (Liu et al., 2021). Against this backdrop, financial sustainability of enterprises has become the key to stable growth. Sustainable financial growth of enterprises is conducive to achieving sales growth and earnings growth, thereby promoting sustainable development of the enterprises (Bui et al., 2020). It is worth noting that the electric power industry, as the most important basic energy industry in a country's economic entity, its operating status directly affects the carbon emission intensity of the power production and supply chain. As the largest carbon emitter, China's slowing

economic growth and improving economic quality have also brought about changes in its economic structure. Therefore, using Chinese enterprises as research samples to study the financial sustainable growth of electric power industry has important reference significance for understanding carbon emissions and carbon peaking.

Financial sustainable growth of enterprises means the increase in assets. While the capital structure remains unchanged, the liabilities and equity of enterprises increase proportionally (Huerga and Rodríguez-Monroy, 2019). In recent years, with the progress of big data analysis, artificial intelligence and other high-tech, not only the traditional financial industries such as banks and securities institutions have ushered in technological changes, but also a number of new financial ecological industries have emerged, and fintech has developed rapidly (Abad-Segura et al., 2020). The fintech provides funding for corporate debt and is an important guarantee for achieving financial sustainability. Existing literature has shown that fintech can compensate for the shortcomings of traditional financial systems such as high service costs and low service efficiency, and improve the financing environment of enterprises (Feng et al., 2022). In addition, the emerging financial ecosystem brought about by fintech has included individual consumers who have been excluded from traditional finance in the scope of financial services, alleviating consumer liquidity constraint, increasing consumer consumption tendencies, and optimizing the business environment faced by enterprises. These studies provide a theoretical basis for fintech to better serve the sustainable financial growth of enterprises. However, there is still a lack of relatively complete empirical evidence on the issue of fintech driven sustainable growth in corporate finance (Li and Jiang, 2021).

Fintech involves many new digital technologies (Puschmann, 2017). For instance, through digital payments, blockchain technology, and supply chain finance, fintech can improve financial efficiency (Wu et al., 2023), reduce costs, and provide greater transparency for enterprises. Research in this area underscores the potential of fintech in promoting corporate financial sustainability. Fintech plays a pivotal role in enterprise risk management, which is crucial for sustainability. Research indicates that fintech tools such as big data analytics and artificial intelligence aid in better identifying, quantifying, and managing environmental, social, and governance (ESG) risks (Du et al., 2022), thereby improving corporate sustainability performance (Arner et al., 2020). Green fintech has become a significant driver of sustainable investments (Macchiavello and Siri, 2022; Merello et al., 2022). Literature covers how fintech facilitates the integration of environmental, social, and governance (ESG) criteria into investment decisions. It also examines the role of fintech platforms in supporting green bonds, impact investing, and the allocation of capital to sustainable projects. Fintech is seen as a means to enhance financial inclusion, which is directly related to sustainable economic development. Research explores how fintech innovations (Lagna and Ravishankar, 2022), including digital lending and mobile banking, can extend financial services to underserved populations, thereby contributing to inclusive growth and corporate social responsibility (Ediagbonya and Tioluwani, 2023). Fintech adoption often leads to digital transformation in corporate finance, resulting in increased efficiency and reduced operational costs (Alt et al., 2018). This stream of research emphasizes how fintech can optimize financial processes, reduce paper-based transactions, and streamline corporate finance operations, all of which are integral to financial sustainability (Dhiaf et al., 2022). In conclusion, the literature on the relationship between fintech and corporate financial sustainability demonstrates that fintech innovations have the potential to bring about positive changes in various aspects of corporate finance. From risk management and sustainable investing to regulatory considerations and financial inclusion, fintech is increasingly recognized as a key enabler of corporate financial sustainability. Further research in this area continues to be vital in understanding the evolving role of fintech in the corporate sustainability landscape.

Reviewing current research, many articles have focused on the measurement and development characteristics of fintech (Pollari, 2016; Suryono et al., 2020). But overall, most articles have certain limitations in measuring the fintech indicator. Some scholars use digital inclusive finance to calculate, but this practice confuses the concepts of fintech and digital inclusive finance. The fintech focus on the latest technological means, while the digital inclusive finance utilizes digital technology and financial means. In addition, the data of digital inclusive finance stems from finite databases and has a small coverage, which cannot comprehensively measure the development level of fintech. Although some scholars have begun to use search engine indices to measure regional fintech levels (Sheng and Fan, 2020), these studies mostly explore the impact of fintech on enterprise innovation (Wang et al., 2023). There is still a lack of empirical evidence on the relationship between the level of fintech and the financial sustainability of electric power industry. Given that the innovation in the electric power industry will have positive effects on the economy and environment, it is worth exploring how the development of fintech can affect the financial sustainability of the electric power industry.

To compensate for the shortcomings of many studies in measuring the level of fintech, this article uses web crawler technology to obtain fintech related search indices to construct a fintech indicator system. On this basis, we used data from A-share listed companies of electric power industry from 2010 to 2020 to examine the impact of fintech on corporate financial sustainability. The reason for choosing this time range for research is that there are the most enterprises with necessary variable data during that period. In order to provide sufficient depth for the research, we also explored the driving channels for the impact of fintech on financial sustainability. Besides, this article also conducts heterogeneity analysis, which has important reference significance for different types of power enterprises to develop their fintech level.

The contributions of this research are as follows. Firstly, regarding the impact of fintech on corporate financial sustainability, this article focuses its research perspective on the power industry, which is not available in most literature. The research results can provide momentous guide for the financial sustainability development of power enterprises and even the basic energy industry. Secondly, existing literature often examines the impact of internal conditions such as enterprise innovation, corporate governance, or financing environment on financial sustainability. As an important external condition for enterprise development, there are not many articles on the relationship between fintech and financial sustainability. Our results enrich the perspective of existing research. From the perspective of enterprise risk, operating income, and financing constraints, this paper reveals their role in the impact of fintech on sustainable financial growth of enterprises, and further clarifies the mechanism of fintech progress on corporate financial sustainability.

The remainder of this paper is arranged as follows. Section 2 is data specifications, theoretical methods and models. Section 3 introduces the analysis of empirical results. Section 4 discusses the impact of empirical results on governments, financial institutions, and enterprises. Section 5 is the conclusion.

2 Literature review and research hypotheses

Fintech establishes effective risk sharing mechanism and provides safeguard for enterprise development (Zhang and Wang, 2021). With the support of high-tech technologies such as cloud computing, fintech can quickly collect and intelligently classify massive amounts of information in the market. And through powerful data processing capabilities, this unstructured information can be structured and transformed, making it easy for information demanders to use (Tang et al., 2020). With the help of precise and reliable information resources, on the one hand, it reduces the probability of the enterprise facing unknown risks, and on the other hand, it improves shareholders' understanding of the daily operation status of the enterprise. From this perspective, fintech can improve the risk-taking ability of enterprises. Driven by interests, enterprises with higher risk-taking capacity will increase their investment in high-yield projects. For example, enterprises with higher risk-taking ability will introduce new technologies and make innovative investments, so as to improve their performance (Luu and Ngo, 2019) and financial sustainable growth.

Through the above analysis, we propose hypothesis 1: the fintech can improve the financial sustainability of enterprises by enhancing their risk-taking ability.

Existing research have shown that fintech can increase operating income of enterprises. On the one hand, because of the transmission of financial information, enterprises can accurately grasp customer needs through the information shared by financial institutions, thereby adjusting marketing strategies and increasing operating revenue (Luo et al., 2022). On the other hand, the development of finthch has changed payment methods, such as the emergence of mobile payments. This greatly saves the payment cost of consumers, improves the efficiency of payment (Berger, 2003), and thus stimulates consumption (Li et al., 2020). The ultimate benefit is that the increase in consumer demand promotes corporate income. It is obvious that an increase in business revenue will directly increase the profit margin of enterprise. According to the definition of Eq 1, the financial sustainability level of enterprises will increase.

Therefore, this paper proposes hypothesis 2: fintech can improve financial sustainability growth of enterprises by increasing operating income.

From the financing perspective, fintech has lowered the investment threshold for scattered investors. This will increase the total amount of credit funds for enterprises (Bellardini et al., 2022), thus providing effective financial support for enterprises (Muganyi et al., 2022). On the one hand, fintech can effectively reduce the financing costs of enterprises. The new and high technology brought about by the development of fintech can make the transaction behavior and credit information of enterprises more transparent. Therefore, such technologies can effectively evaluate corporate reputation and alleviate information asymmetry between banks and enterprises (Duarte et al., 2012; Cheng et al., 2014). This will reduce various information costs for both sides of the credit transaction (Heiskanen, 2017), thereby improving the financing environment. On the other hand, fintech can create more new financing modes. With the support of big data, blockchain and other technologies, a series of online financing ways have emerged (Buchak et al., 2018; Jagtiani and Lemieux, 2018). More financing channels will bring more credit funds to enterprises on the edge of the financial system, especially small and medium-sized enterprises. The direct advantage of improving the financing environment is the increase of the equity multiplier of enterprises, thus reducing the financial risk of enterprises.

In view of this, we propose hypothesis 3: the fintech can improve the financial sustainability of enterprises by improving financing constraints.

3 Data and models

3.1 Econometric model

Referring to Nanda and Rhodes-Kropf (2013), we construct the following econometric model:

$$SGR_{it} = \alpha + \beta fintech_{kt} + \gamma controls + \phi_i + \varphi_t + \varepsilon_{it} \quad (1)$$

In Eq 1, we added a city attribute to each business sample, based on the location of the business. SGR_{it} represents the financial sustainable growth of company i in the t-th year. $fintech_{kt}$ is the financial technology development level of city k where enterprise i is located in the t-th year. *controls* represents a vector of a set of control variables, including fixed asset ratio (*far*), government subsidy (*subsidy*), enterprise size (*size*), corporate leverage (*leverage*), regional economic level (*lnrgdp*), and scientific research input and education input (*input*). ϕ_i represents the fixed effect of the company, and the fixed effect of the region is absorbed by this effect. φ_t is the time fixed effect and ε_{it} is the random error term.

In order to explore the reasons why fintech affects financial sustainable growth of enterprise, this paper constructs the following mediating effect model:

$$SGR_{it} = \alpha_0 + \alpha_1 fintech_{kt} + \alpha_2 controls + \phi_i + \varphi_t + \varepsilon_{it} \quad (2)$$

$$mediator_{it} = \beta_0 + \beta_1 fintech_{kt} + \beta_2 controls + \phi_i + \varphi_t + \varepsilon_{it} \quad (3)$$

$$SGR_{it} = \lambda_0 + \lambda_1 fintech_{kt} + \lambda_2 mediator_{it} + \lambda_3 controls + \phi_i + \varphi_t + \varepsilon_{it} \quad (4)$$

In Eqs 3, 4, *mediator* represents a mediator variable, corporate risk-taking ability (*risk*), or operating income (*income*), or financing constraints (*constraints*). The meanings of other parameters in Eqs 2–4 are the same as those in Eq 1. Based on the concept of causal progressive regression, if β_1 and λ_2 are statistically significant, then there is the mediating effect.

3.2 Variable selection and design

3.2.1 Dependent variable

The usual models for measuring sustainable financial growth of enterprises are divided into two categories: accounting and cash

flow. Compared to the calculation method of cash flow, using accounting standards is more accurate. This is because the factors that affect accounting profits are more stable. Referring to Liu and Xie. (2021), this article uses the Van Horne model to calculate the sustainable financial growth of enterprises. This model relaxed the assumption that new shares cannot be issued, which is more in line with the actual state of operation of the enterprises. The calculation formula is as follows:

$$SGR_{it} = \frac{profit_{it} \times retention_{it} \times (1 + PPR_{it})}{1/turnover_{it} - inrate_{it} \times retention_{it} \times (1 + PPR_{it})} \quad (5)$$

In Eq 5, *i* represents the year and *t* represents the enterprise. *SGR* is the sustainable financial growth of enterprise. *profit* is sales net profit, *retention* is the retention rate of income, and *PPR* is the proportion of property right. *turnover* is designated as the ratio of total assets turnover and *inrate* is the net profit margin on sales.

3.2.2 Independent variable

Refer to Li et al. (2020), this article selects 48 keywords related to fintech: EB level storage, NFC payment, Cloud computing, Internet finance, Artificial intelligence, Billion-level concurrency, Cyber-physical system, Memory computing, Distributed computing, Blockchain, Business intelligent, Image understanding, Graph Processing, Secure multi-party computation, Big data, Differential privacy technology, Open Bank, Heterogeneous data, Credit investigation, Investment decision support system, Digital currency, Data visualization, Web data mining, Text mining, Intelligent customer service, Intelligent investment advisor, Intelligent data analysis, Smart finance contract, Machine learning, Stream computing, Deep learning, The Internet of things, Biometrics, Mobile internet, Mobile payment, Third-party payment, Brain-inspired computing, Green computing, Online UnionPay, Equity crowdfunding financing, Natural language processing, Virtual reality, Fusion Architecture, Cognitive computing, Semantic search, Speech recognition, Authentication, Quantitative finance. Using web crawler technology, we count the number of news pages with cities and the above keywords by year in Baidu News Advanced Search. Next, add up the total number of search results for 48 keywords in each city and year. Due to the distribution of this indicator is significantly right-skewed, this paper performs a logarithmic transformation on this indicator to obtain the final fintech index.

3.2.3 Control variables

To alleviate estimation bias caused by missing explanatory variables, referring to (Wang et al., 2023), a series of control variables at the enterprise and regional levels are also included in the construction of the econometric models: in the enterprise level, fixed asset ratio (*far*), government subsidy (*subsidy*), enterprise size (*size*), corporate leverage (*leverage*); in the regional level: regional economic level (*lnrgdp*), scientific research input and education input (*input*). There are two reasons for selecting these control variables. The first is to avoid endogeneity issues with the independent variable, that is, some variables are related to both the dependent variable and the variable of interest. If not controlled, endogeneity issues may arise with the variable of interest. The second is to minimize the estimation bias of the concerned variables as much as possible. In addition, this article also selected three types of mediating variables for the study of impact mechanisms, they are corporate risk-taking ability (*risk*), operating income (*income*), and financing constraints[1] (*constraints*), respectively. The theoretical analysis of the impact mechanism of these three mediating variables will be elaborated in Section 3. The specifications for all variables selected in this article are shown in Table 1.

To make the estimation results more reliable, we first exclude companies with abnormal financial conditions and delisting risks, then remove samples with missing data in the main variables, and finally perform the winsorize on continuous variable data with upper and lower limits of 1%.

3.3 Descriptive statistics

Table 2 reports the basic statistical characteristics of the main variables. The minimum value for *SGR* is −0.017, and the maximum value is 0.135. This indicates that there are relatively apparent differences in the sustainable financial growth of enterprises in our sample. It is noteworthy that the difference between the mean and the median for each variable is not very large, the range for *subsidy* is 1.594, and the range for *lnrgdp* is 5.703. This indicates that there is no significant skewness in the data of all variables. In addition, we also visualized the average level of fintech in each city during the sample period, the results are shown in Figure 1. It can be seen that there is a significant geographical distribution difference in the level of financial technology, and the closer it is to coastal areas, the higher its value, especially in Beijing and Shanghai.

4 Results and analysis

4.1 Baseline regressions analysis

Table 3 reports on the impact of fintech on the financial sustainable growth of electric power enterprises. The first column shows the regression results that only include the explanatory variable *fintech*. Compared to the first column, the result in the second column has an apparent increase in R-squared after adding control variables. The coefficient of *fintech* is significantly positive in both types of regressions, this indicates the positive effect of the fintech development on the financial sustainability of electric power enterprises.

The development of enterprises cannot do without the support of financial institutions. Under the traditional financial model, enterprises find it difficult and expensive to obtain more external funds for production due to difficulties in financing, which has a constraining effect on their development. With the rapid rise of digital technology, it has rapidly integrated with various industries, effectively promoting the development of digital finance. The

1 Referring to Kaplan and Zingales. (1997), this article calculates the financing constraint index. The larger the index, the greater the degree of financing constraints faced by the enterprise.

TABLE 1 Data specifications.

Variables	Explanations	Unit	Data source
SGR	sustainable financial growth of enterprise	Index	CSMAR and WIND databases
fintech	financial technology	Index	CSMAR and WIND databases
far	fixed assets/total assets at the end of the year	%	CSMAR and WIND databases
subsidy	government subsidies/total assets	%	CSMAR and WIND databases
size	enterprise size: the logarithm of the total assets of the enterprise	Constant 10^6 USD	CSMAR and WIND databases
leverage	corporate leverage: total liabilities/total assets	%	CSMAR and WIND databases
lnrgdp	the logarithm of *per capita* GDP in the city where the enterprise is located	Constant 10^8 USD	China City Statistical Yearbook
input	scientific research input and education input	Constant 10^8 USD	China City Statistical Yearbook
risk	corporate risk-taking ability: standard deviation of monthly stock returns within a year	Index	CSMAR and WIND databases
income	operating income/total assets	%	CSMAR and WIND databases
constraints	financing constraint	Index	CSMAR and WIND databases

TABLE 2 Descriptive statistics.

Variables	N	Mean	Std	Min	Median	Max
SGR	2365	0.043	0.075	−0.017	0.039	0.135
fintech	2365	4.075	0.966	2.565	3.989	6.574
far	2365	0.335	0.128	0.000	0.293	0.698
subsidy	2365	0.647	0.852	0.000	0.392	1.986
size	2365	18.174	3.367	9.867	16.235	35.689
leverage	2365	0.324	0.186	0.062	0.302	0.967
lnrgdp	2365	2.289	0.592	1.523	1.876	7.579
input	2365	2.193	2.539	0.959	2.541	13.312
risk	2365	1.568	0.739	0.295	1.731	3.489
income	2365	0.498	0.112	0.124	0.689	1.237
constraints	2365	1.279	1.468	−58.246	1.859	11.329

financing problems of enterprises have also been effectively alleviated, making it easier for enterprises to obtain more financing funds than before.

There is also a certain relationship between control variables and financial sustainability. The coefficient of *subsidy* is positive and reaches a significance level of 5%, indicating that government subsidies are beneficial for sustainable financial growth of enterprises. The coefficients of *size* and *input* are positive and reach a significance level of 1%. This indicates that the financial sustainability level of large enterprises is relatively better, and the financial sustainability of enterprises is stronger in cities with higher levels of science and education.

4.2 Analysis of impact mechanism

Table 4 is the regression results using the corporate risk-taking ability (*risk*) as a mediator variable. The regression results of columns (1), (2), and (3) correspond to the models in Eqs 3–5, respectively. The coefficient of *fintech* in column (2) is positive at a significance level of 5%, indicating that fintech can improve the risk-taking ability of electric power enterprises. The coefficient of *fintech* in column (3) is positive at a significance level of 1%, we can think that the risk-taking ability has played a part of the mediating effect between fintech and corporate financial sustainability. In other words, the improvement of fintech level of electric power enterprises can promote their sustainable financial growth by enhancing their risk resistance ability.

Table 5 reports the regression results using the operating income (*income*) as a mediator variable. For the results in column (2), the coefficient of *fintech* is positive at a significance level of 10%, indicating that fintech can stimulate the increase of operating income for enterprises. The results in column (3) indicate that after adding the mediator variable *income*, the coefficient of *fintech* remains positive at a significance level of 1%. This shows that the operating income of enterprises has played a part of the mediating effect in the impact of fintech on corporate financial sustainability. The increase in operating income will result in more cash flow for the enterprises (Fairfield et al., 2003), and enterprises have more funds to upgrade products, technologies, and systems of organization. This will improve the operational efficiency of the enterprise, thereby promoting financial sustainable growth.

Table 6 shows the regression results using the financing constraints (*constraints*) as a mediator variable. Similar to previous analysis, the coefficient of *fintech* in column (2) is negative at a significance level of 1%, indicating that fintech can relieve financing constraints of electric power enterprises. For the results in column (3), the coefficient of *fintech* is significantly positive and the coefficient of the mediating variable remains significantly negative. This proves that for electric power enterprises, the financing constraints has played a part of the mediating effect between fintech and corporate financial sustainability. One possible explanation is that with the improvement of the financing environment, enterprises have more funds to participate in projects with high returns but long cycles, thereby increasing their profits and promoting financial sustainable growth.

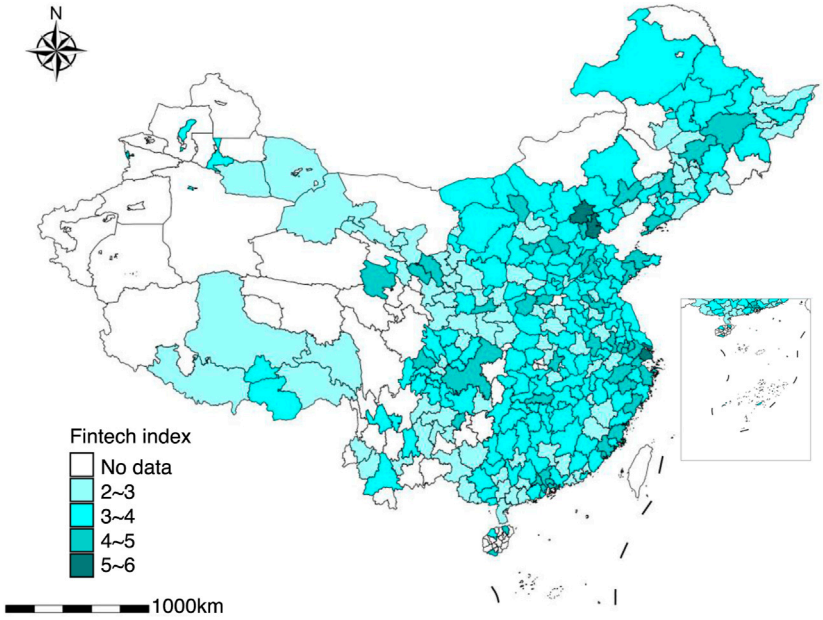


FIGURE 1
The spatial distribution of the average level of fintech between 2010 and 2020.

TABLE 3 Results of baseline regressions.

Variables	(1)	(2)
fintech	0.012***	0.008***
	(0.004)	(0.001)
far		−0.035
		(0.029)
subsidy		0.033**
		(0.018)
size		0.017***
		(0.003)
leverage		−0.019
		(0.022)
lnrgdp		0.023
		(0.034)
input		0.076***
		(0.016)
Individual F-E	Yes	Yes
Time F-E	Yes	Yes
R^2	0.023	0.107
N	2365	2365

Note: ***, **, * represent statistical significance at 1%, 5%, 10% level respectively, standard error in parenthesis is clustered to the enterprise level, the same as in the following table.

TABLE 4 The regression results using *risk* as a mediator variable.

Variables	(1)	(2)	(3)
	SGR	*risk*	*SGR*
fintech	0.008***	0.021**	0.007***
	(0.003)	(0.012)	(0.002)
risk			0.003**
			(0.002)
far	−0.035	0.127	−0.084
	(0.102)	(0.098)	(0.069)
subsidy	0.033**	−0.047***	0.015***
	(0.018)	(0.014)	(0.003)
size	0.017***	0.026***	0.009***
	(0.005)	(0.009)	(0.003)
leverage	−0.019	−0.056**	−0.002
	(0.013)	(0.030)	(0.004)
lnrgdp	0.023	−0.014	0.051
	(0.029)	(0.023)	(0.042)
input	0.076***	0.029**	0.011**
	(0.019)	(0.007)	(0.006)
Individual F-E	Yes	Yes	Yes
Time F-E	Yes	Yes	Yes
R^2	0.107	0.184	0.109
N	2365	2365	2365

TABLE 5 The regression results using *income* as a mediator variable.

Variables	(1)	(2)	(3)
	SGR	*income*	*SGR*
fintech	0.008***	0.003*	0.008***
	(0.003)	(0.001)	(0.003)
income			0.007*
			(0.004)
far	−0.035	−0.057	−0.039
	(0.022)	(0.048)	(0.027)
subsidy	0.033**	0.148***	0.057***
	(0.018)	(0.054)	(0.012)
size	0.017***	−0.059***	0.148***
	(0.008)	(0.000)	(0.000)
leverage	−0.019	−0.024	−0.060
	(0.012)	(0.049)	(0.051)
lnrgdp	0.023	−0.025**	0.009*
	(0.029)	(0.012)	(0.005)
input	0.076***	0.027***	0.048***
	(0.021)	(0.010)	(0.013)
Individual F-E	Yes	Yes	Yes
Time F-E	Yes	Yes	Yes
R^2	0.107	0.164	0.129
N	2365	2365	2365

4.3 Heterogeneity analysis

As mentioned earlier, the financing environment faced by small and medium-sized enterprises is often more severe. According to the results in Table 6, the financing environment has a mediating effect. This means that there are often differences in financial conditions for enterprises of different sizes. So, is there a difference in the impact of fintech on financial sustainable growth for enterprises of different sizes? Based on the median of enterprise size (*size*), we divide the research samples into two groups for regression and comparison. The results are shown in columns (1) and (2) of Table 7. The coefficient of *fintech* in column (1) is positive at a significance level of 1%, but the *p*-value of the coefficient in column (2) is 0.103. This indicates that for smaller power companies, the development of fintech can better improve their financial sustainability. This is mainly because compared to large enterprises, financing for small and medium-sized enterprises is more difficult (Watson R and Wilson, 2002; Abdulsaleh and Worthington, 2013). But fintech has expanded financing channels, improved the financing environment for small and medium-sized enterprises, and enabled their financial situation to significantly take a turn for the better.

The data of electric power enterprises selected in this paper come from two industries, the power generation industry and the electrical equipment manufacturing industry. So, is there a significant difference in the impact of fintech on financial sustainability between these two industries? The samples belonging to the two industries are respectively used for regression estimation. Column (3) in Table 7 shows the regression results belonging to the power generation industry, while column (4) shows the regression results of the electrical equipment manufacturing industry. It can be seen that the coefficient of *fintech* is significantly positive in both columns (3) and (4), indicating that the difference between the two industries is not very conspicuous. This may be because both industries belong to technology intensive industries, which have long technology and equipment development cycles and high demand for capital investment. Fintech provides a favorable financing environment and stronger risk-taking ability for these types of enterprises, which significantly promotes their financial sustainable growth.

In terms of financing environment there is a widespread phenomenon of "ownership discrimination" in the financial market. Compared to private enterprises, state-owned enterprises are often more likely to receive financial support (Poncet et al., 2010; Guariglia et al., 2011). For example, Cull et al. (2009) found that even though some state-owned enterprises have low profitability, they are still more likely to obtain loans from banks. As the technology-intensive and capital-intensive industries, the situation of ownership discrimination in electric power industry is often more severe.

TABLE 6 The regression results using *constraints* as a mediator variable.

Variables	(1)	(2)	(3)
	SGR	*constraints*	*SGR*
fintech	0.008***	−0.054***	0.005***
	(0.003)	(0.014)	(0.001)
constraints			−0.054**
			(0.014)
far	−0.035	−0.191	−0.082
	(0.029)	(0.210)	(0.125)
subsidy	0.033**	−0.008***	0.009***
	(0.017)	(0.002)	(0.003)
size	0.017***	0.011**	0.028**
	(0.005)	(0.003)	(0.016)
leverage	−0.019	−0.101	−0.038
	(0.032)	(0.119)	(0.027)
lnrgdp	0.023	0.013**	0.038**
	(0.029)	(0.007)	(0.024)
input	0.076***	0.106***	0.091***
	(0.024)	(0.039)	(0.033)
Individual F-E	Yes	Yes	Yes
Time F-E	Yes	Yes	Yes
R^2	0.107	0.211	0.125
N	2365	2365	2365

Therefore, the research samples are divided into two groups for comparison: state-owned enterprises and private enterprises. Column (5) in Table 7 is the regression results belonging to the state-owned enterprises, while column (6) is the regression results of private enterprises. Although the coefficients of both are significant, the effect of fintech on improving the financial sustainability of private enterprises is much greater than that of state-owned enterprises. With the support of network technology, the development of financial technology has expanded financing channels. With the support of network technology, the development of financial technology has expanded financing channels, which to some extent alleviates the phenomenon of ownership discrimination.

4.4 Endogeneity and robustness

The fintech level calculated in this article is at the macro level, so it may lead to endogeneity issues due to variables omission or measurement errors. This way uses two methods to weaken endogeneity to verify the reliability of the conclusion. The first method is that the independent variable is lagged by one period to reevaluate the model, and the other method is the instrumental variable method. According to Chong et al. (2013), the average value of the fintech development level of all neighboring cities in a city in the same year is used as an instrumental variable. This instrumental variable meets the two conditions of correlation and exogeneity. On the one hand, because of the similar economic levels of neighboring cities, the level of fintech is interrelated. On the other hand, due to the regional segmentation of credit financing, fintech of surrounding areas is difficult to affect the financial sustainability of enterprises in local city. Table 8 reports the regression results of two methods. The Hausman test and F-statistic in the first stage are significant, it indicates that the instrumental variable meets the conditions for exogenous and effectiveness. In the regression results of both methods, the coefficients of *fintech* are significantly positive, indicating the reliability of the results in this paper.

To verify the robustness of the estimation results, this article uses the following three methods to re-estimate the model. The first method is to adjust the time range of the sample, we perform regression estimate again with a 1-year lag on the sample. The second method is to exclude samples belonging to financial metropolises, including Beijing, Shanghai, and Shenzhen. The third method is to reevaluate by replacing fintech data from city level to provincial level. The robustness estimation results are shown in Table 9, columns (1)–(3) in the table correspond to the three robustness estimation methods mentioned above, respectively. Regardless of the method, the estimated results are consistent with Table 3. This proves the robustness of the main conclusions in this paper.

TABLE 7 Heterogeneity analysis results.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
fintech	0.017***	0.005	0.007**	0.011***	0.003***	0.026***
	(0.002)	(0.009)	(0.004)	(0.03)	(0.001)	(0.007)
controls	Yes	Yes	Yes	Yes	Yes	Yes
Individual F-E	Yes	Yes	Yes	Yes	Yes	Yes
Time F-E	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.129	0.084	0.119	0.143	0.093	0.117
N	1182	1183	583	1782	1421	944

TABLE 8 Endogenous tests.

Variables	(1)	(2)
fintech	0.011***	0.057**
	(0.004)	(0.022)
controls	Yes	Yes
Individual F-E	Yes	Yes
Time F-E	Yes	Yes
Hausman test	95.79***	102.21***
F-statistic in the first stage	55.33***	62.94***
R^2	0.109	0.136
N	2365	2365

Note: column (1) is the regression result of the independent variable lagging for one period, and column (2) is the regression result by using the instrumental variable.

TABLE 9 Robustness tests.

Variables	(1)	(2)	(3)
fintech	0.009***	0.015***	0.038**
	(0.002)	(0.004)	(0.015)
controls	Yes	Yes	Yes
Individual F-E	Yes	Yes	Yes
Time F-E	Yes	Yes	Yes
R^2	0.145	0.092	0.082
N	2893	1742	2365

5 Implications of the research results

5.1 The perspective of government

As the most important basic energy industry, the sustainable development of electric power industry is related to the stability of a country's economy and society. Based on our mediation effect results, specifically, the government should build diversified financial services industry to achieve precise abutment between finance and enterprises, especially small and medium-sized electric power enterprises. This is beneficial for the electric power industry to obtain financial services at a lower cost and in a more convenient way, and to better exert the advantages of fintech in enhancing economic growth efficiency. In addition, the results in Table 7 show that the impact of fintech on financial sustainability tends to be different for different types of electric power enterprises. While encouraging the development of fintech, it is necessary for the government to identify and protect vulnerable enterprises, and comprehensively promote the positive role of fintech in the electric power industry.

5.2 The perspective of enterprises

The electric power industry should adapt to the trend of the times and strengthen the integration with regional fintech development. The results of Table 3 demonstrate that fintech can promote the financial sustainable growth of electric power companies. Enterprises should make good use of the advantages of fintech development, alleviate financing difficulties, improve their own risk resistance ability, and ensure corporate financial sustainability. Heterogeneity analysis indicates that compared to large and state-owned enterprises, small and medium-sized enterprises and private enterprises are more able to enjoy the financial benefits brought by the development of fintech. This is mainly because small and medium-sized enterprises and private enterprises have always been in a disadvantaged position in the traditional financial system, making it more difficult for them to obtain loans from banks. But the development of fintech can change their financial difficulties. With the support of artificial intelligence, big data, cloud computing and other technologies, a series of new financial products and services have been produced. Therefore, for small and medium-sized enterprises and private enterprises, they should seek more new financing channels through fintech to better achieve their own financial sustainable growth.

5.3 The perspective of financial institutions

Facing the opportunities brought by the development of fintech, traditional financial institutions need to strengthen their integration with emerging technologies. The results of columns (1) and (2) in Table 7 indirectly illustrate the more severe financing environment faced by small and medium-sized enterprises. Traditional financial institutions can ease the financing difficulties of small and medium-sized electric power enterprises through the technology brought by fintech. For example, by building open banks, connecting financial services with commercial cooperation, providing diversified and high-quality financing channels for small and medium-sized enterprises. Analysis of impact mechanism in this paper indicates that fintech can promote the financial sustainable growth of electric power enterprises by reducing financing constraints and enhancing risk-taking ability. Therefore, in the process of technological transformation, financial institutions can focus on the reform at the credit and insurance aspects, lower the threshold for financial services, and innovate more credit and insurance products.

6 Conclusion and outlook

This paper explores the impact mechanism of fintech on the financial sustainable growth of electric power enterprises. After extracting 48 fintech related keywords, we construct a regional fintech indicator system using web crawler technology. On this basis, we used data from A-share listed companies of electric power industry from 2010 to 2020 to build the econometric model that includes both enterprise and regional levels. The results indicate that fintech has significantly improved the financial sustainability of electric power enterprises. Further exploration finds that fintech can promote financial sustainable development by enhancing corporate risk-taking

ability, increasing operating income, and alleviating financing constraints.

Heterogeneity analysis indicates that ownership discrimination still exists in electric power enterprises. Private enterprises can obtain more credit funds through new financing channels opened by financial technology. So compared to state-owned enterprises, fintech has a more significant effect on improving the financial sustainability of private enterprises. In addition, fintech is more significant in helping small and medium-sized electric-power enterprises in financial sustainability, while it is less helpful for large enterprises. The results of robustness and endogeneity tests show that the research results of this article are reliable.

Because of the difficulty in obtaining data, this study only takes China as an example to explore the impact of fintech on the financial sustainability of the electric power industry. In the future, we can obtain data from more countries to seek more universally applicable conclusions. In addition, we only analysis three potential paths for fintech to improve financial sustainability. Therefore, more impact mechanisms can be found through data from more countries.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

LQ: Conceptualization, Methodology, Project administration, Resources, Writing–review and editing. ML: Conceptualization, Data curation, Methodology, Software, Writing–original draft.

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Conflict of interest

Authors LQ and ML were employed by State Grid Jiangsu Electric Power Co., Ltd.

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Impact of environmental regulation on government subsides of public-private partnership waste-to-energy incineration projects: evidence from 66 cities in China

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Introduction: Environmental regulation, as a vital component of public regulation in China, plays a crucial role in coordinating regional eco-efficiency, while the traditional hypothesis, Porter hypothesis, and uncertainty hypothesis offer three different perspectives for understanding the relationship between industry performance and environmental regulations.

Methods: Based on the assumption of industry heterogeneity, 81 public-private partnership (PPP) waste-to-energy (WTE) incineration projects are analyzed using panel data from 66 cities within China during the period from 2013 to 2017 with the aims to reveal the underlying mechanism behind environmental regulation and the government subsides of public-private partnership waste-to-energy incineration projects by using multiple regression modeling.

Results: The results show that the impact of environmental regulation on government subsides of PPP WTE projects has demonstrated an "Inverted-U"-shaped relationship with an inflection point, of which an increase in environmental regulation is positively correlated with an increase in subsidies at first then a negative correlation developing later.

Discussion: The findings are significant in setting flexible environmental regulations according to the needs of regional economic and social development. In addition, they also supply a theoretical reference for promoting the WTE incineration industry's sustainable and healthy development.

KEYWORDS

environmental regulation, public private partnerships, waste-to-energy incineration project, government subsides, impact

1 Introduction

Waste-to-energy (WTE) technologies currently play a prominent role in the disposal of Municipal Solid Waste (MSW). First, they provide an effective and sustainable means of eliminating MSW and solve the problem of "garbage siege", hence alleviating pressure on urban land (Lu et al., 2018; Ding et al., 2021). Second, a large amount of heat is produced during waste combustion that further promotes renewable energy generation (heat and/or power, gases, etc.) (Francesco et al., 2018; Kamyab et al., 2022). Third, compared to anaerobic digestion and aerobic composting technology, WTE stands out as an optimal approach for efficiently treating MSW in a shorter time, at a lower cost and with well-established technology, and it excels in handling inorganic waste, which anaerobic composting and aerobic digestion technology cannot achieve (LoRe and Hurdle, 2013; Qazi et al., 2018). These advantages of WTE incineration have led to its worldwide popularity in recent decades, contributing greatly to the sustainable development of the circular economy and society (Leckner, 2015; Istrate et al., 2020; Peng et al., 2023). In China, almost all WTE incineration projects are constructed and developed through Public-Private Partnership (PPP) arrangements, which rapidly promotes the MSW disposal capacity while greatly improves their operational efficiency (Sastoque et al., 2016; Hou et al., 2022). It is estimated that 108 WTE incineration projects were deployed by PPPs from May 2012 to January 2017 in China with a total investment of CNY 489 billion, accounting for over 70% of the whole WTE incineration project library (Song et al., 2017).

Currently, revenue from PPP WTE incineration projects in China is mainly comprised of two parts: namely, government subsidies and the income from electricity sales. According to *the Notice of the National Development and Reform Commission on Adjusting Electricity Prices* (*No. 801 [2012]*) (National Development and Reform Commission, 2012), the benchmark price of electricity sold by these incinerators has been standardized to set level (0.65 CNY/kwh, 280kwh/t) since 2013. Correspondingly, the subsidies paid by the local government for MSW disposal have played a vital role in the financial feasibility of PPP WTE incinerators. Li et al. (2016) currently revealed that nearly half of the revenue generated by these projects is from government subsidies. However, there are huge differences between the government subsidies for different projects in different regions in China. For instance, the government subsidy for the Qingzhen PPP WTE incineration project in Guiyang was CNY 142/t in 2016, while it was CNY 54.6/t for the Xinyang PPP WTE incineration project in Henan in the same period (See www.ccgp.gov.cn). Thus, it is important to provide an insight into this phenomenon and clarify the influencing factors of the government subsidies involved, as well as studying the associated influencing mechanisms.

Previous studies indicate that the government subsides of PPP WTE incineration projects are influenced by multiple factors, such as project scale (Song et al., 2017; Cao et al., 2022), regional economic and social characteristics (Zhao et al., 2016), and environmental regulation (Li et al., 2015; Fu et al., 2021). Specifically, relevant studies show that environmental regulation plays a vital role in industry performance, especially in pollution-intensive industries (Zhou et al., 2017; Zou and Zhang, 2022). However, the specific impact of environmental regulation on the PPP WTE incineration industry's government subsides remains unclear. Meanwhile, despite ample research on the impact of environmental regulation on industrial performance, its underlying mechanism is debatable (Yuan et al., 2017; Zhang et al., 2019). Moreover, although the influencing mechanism of environmental regulation has been discussed intensively in similar industries, such as sewage treatment (Khaliq et al., 2017; Pan and Tang, 2021) and coal mines (Dzonzi-Undi and Li, 2015; Jia and Luo, 2023), further verification is still needed of the specific impact of environmental regulation on the PPP WTE incineration industry because the impact of environmental regulations on industrial performance varies between different industries (Liu et al., 2020; Luo et al., 2021).

To bridge this research gap, the present study aims to understand the impact of environmental regulation on government subsides of PPP WTE incineration projects using a multiple regression model based on panel data from 81 such projects distributed over 66 Chinese cities from 2013 to 2017. The findings enrich the literature related to environmental regulation and industrial performance in China, as well as addressing the research gap in the WTE incineration industry. Moreover, it is conducive to the developing of suitable policies, and beneficial for companies in formulating separate development strategies.

2 Literature review

2.1 Environmental regulation

Environmental regulation, as a vital component of public regulation, is an effective approach to adjust market failure and has made a significant approach towards the coordinated development of China's economic development and environmental protection (Galinato and Chouinard, 2018; Wang et al., 2020; Shi et al., 2023). Environmental regulation is necessary because of the negative externalities of environmental pollution and the nature of environmental public goods. It is generally categorized into three types: command-and-control instruments, market-based instruments, and voluntary instruments (Ren et al., 2016). Of these, the use of command-and-control instruments imposed by administrative agencies is the most widely adopted approach today (Kostka, 2016; Xie et al., 2017; Shen et al., 2019). In addition, due to the imbalance of regional environmental conditions in China and economic and social development, the stringency of environmental regulations differs in different regions (Zhang et al., 2019; Rong et al., 2023).

Under the constraints of environmental regulation, companies need to pay additional costs to ensure environmental compliance, which affects their market competitiveness (Zhao and Sun, 2016; Song et al., 2022). Hence, the impact of environmental regulation on different industries has attracted great interest in both academia and industry (Vormedal and Skjaerseth, 2020; Du et al., 2021). Currently, there are three mainstream theories regarding this issue: namely, the *traditional hypothesis*, the *Porter hypothesis*, and the *uncertainty hypothesis*. The traditional hypothesis suggests that environmental regulation has a negative impact on industry performance because high environmental standards may cause unemployment and a decline in productivity due to the

additional costs incurred by environmental regulations (Conrad and Wastl, 1995; Jaffe and Stavins, 1995). Porter and Linde (1995), on the other hand, insist that environmental regulation is able to strengthen company innovation and then improve industry performance–arguing that properly designed environmental regulations can catalyze innovations, which may offset the cost of compliance costs and generate new competitive advantages (Porter and Linde, 1995). Moreover, according to Yuan and Xiang (2018) and Zhang et al. (2019), for instance, the relationship between environmental regulation and industry performance is non-linear, which should take various factors into consideration, such as innovation, capital, and industrial policies (Stavropoulos et al., 2018).

To measure the intensity of environmental regulation in different regions, studies have developed a variety of indicator systems, mainly comprising input indicators, performance-based indicators, and exponential indicators (Chen and Wu, 2018). The *input indicators* emphasize the cost paid by companies to meet environmental regulation standards, such as the investment in pollution treatment, expenditure on pollution reduction, and the cost of supervision. Chen and Cheng. (2017) measures the stringency of environmental regulation experienced by various companies by operating costs and investment in equipment related to environmental protection. In contrast, *performance-based indicators* measure the stringency of environmental regulation through the environmental outcomes of a company. Domazlicky and Weber (2004), for instance, indicate that environmental regulation can be evaluated from different types of pollution, such as SO_2 and NO_x emissions and waste-water discharge–holding that the higher the intensity of pollutants emission, the stricter will be the environmental regulation measures taken by the government (Ravetti et al., 2016; Li et al., 2022; Yang et al., 2022). Nevertheless, some studies contend that a comprehensive indicator system should be built to better reflect the stringency of environmental regulation (Botta and Koźluk, 2014; Wang et al., 2022). Tobey (1990), for example, conducted an empirical test to measure the stringency of environmental regulation in developing and developed countries by constructing *exponential indicators* and concluded that developed countries have stricter environmental standards in pollutant emissions. In 1997, Beers et al. (1997) further enriched the exponential indicators system by adding several narrow indicators. So far, a comprehensive set of exponential indicators have been developed and widely used to measure the stringency of environmental regulation (Zhao et al., 2019).

2.2 Government subsides of PPP WTE incineration projects

WTE face issues such as low processing efficiency and high construction and operation costs (Batista et al., 2021). To address the problems, the National Development and Reform Commission have issued the "the Implementation Plan of Domestic Waste Classification System" and "the National Action Plan for the Prevention and Control of Environmental Pollution by Solid Waste". The government attaches great importance to the problem of waste disposal, putting it on the national agenda, and setting up special subsidies. The purpose of government subsidies is to promote enterprises to invest and innovate by providing financial support. It becomes evident that government subsidies play a pivotal role in ensuring the sustainable development of waste management (Guo et al., 2022). Government subsidies of PPP WTE incinerators refer to the money paid by local government for every tonne of MSW disposed, this is one of the most important incomes derived by PPP WTE incinerators and is of great significance in the WTE industry's development (Li et al., 2015). In contrast with electricity prices, the waste disposal subsidy in China is mainly determined through market competition and bidding, and there is no uniform standard. Table 1 lists some representative PPP WTE incineration projects and their corresponding government subsidies.

As indicated, the government subsidies vary widely between different projects, with the largest difference being almost triple. In practice, the gap in government subsidies is even more prominent. Relevant research reveals that various key factors are involved, such as location, scale of incinerator, technological innovation, and environmental regulation (Zhang et al., 2014; Chen et al., 2021). Of those, the regional urbanization level and the level of economic development are recognized as crucial factors affecting the industry's performance. Some studies show that the government subsidies in China's eastern developed areas are generally higher than the central land western regions (Zhao et al., 2016; Yu et al., 2020). Meanwhile, the scale of the incinerator can also affect the government subsidy through daily waste treatment capacity (Song et al., 2015). In addition, compared with landfill, the WTE incineration industry is an important high-tech industry and Mi et al. (2018) points out that technological innovation can effectively improve the competitiveness of WTE incinerators, which is beneficial to industry performance. There are also some studies argue that the level of regional education development is significant in shaping the attitudes and actions of local communities (Liu et al., 2018), and the construction of WTE incinerators in low socioeconomic areas would increase their operating costs.

2.3 Association between environmental regulation and government subsidies of PPP WTE incineration projects

Currently, environmental regulations have proved to be an increasingly leading factor in the pollution-intensive industries (Zhang et al., 2020), with three different theoretical perspectives of the effect of environmental regulations upon industry performance-the traditional hypothesis, the Porter hypothesis and the uncertainty hypothesis. However, the heterogeneity of industries means that environmental regulations may have different effects between different industries (Martin, 2010; Shen et al., 2019), although many studies have already explored the association between environmental regulation and such pollution-intensive industries as the chemical industry (Wang et al., 2015) and sewage treatment (Khaliq et al., 2017), little attention in the literature has been paid to the PPP WTE incineration industry.

Over the past decade, to further develop the PPP WTE incineration industries, the Chinese government has issued a series of environmental regulations. In particular, in 2012, the "*Notice of the National Development and Reform Commission on*

TABLE 1 The government subsidies of representative PPP WTE incineration projects.

Year	Province	Projects	Subsidies (CNY/t)
2017	Fujian	The Nanping PPP WTE incineration Plant	76
2017	Guangdong	The Xuwen BOT WTE incineration Plant	80.5
2016	Guizhou	The Qingzhen PPP WTE incineration Plant	142
2017	Jiangsu	The Jiangdu PPP WTE incineration Plant	85
2017	Jiangxi	The Yingtan PPP WTE incineration Plant	68
2017	Shandong	The Wendeng PPP WTE incineration Plant	52
2014	Zhejiang	The Hangzhou Jiufeng PPP WTE incineration Plant	108

TABLE 2 Definitions of the independent variables.

Type	Variable	Name	Definition
Independent variable	WW	Wastewater discharge intensity	Wastewater discharge intensity = Wastewater quantity/GDP
	WG	Waste gas emission intensity	Waste gas emission intensity = SO_2/GDP
	SW	Solid waste's comprehensive utilization rate	Solid waste's comprehensive utilization rate = utilization of solid waste/production of solid waste

Adjusting Electricity Prices (*No. 801 [2012]*)" standardized the benchmark price of electricity sold by the industry. Now that electricity sales income is stable and the scale of PPP WTE incineration projects is clear, government subsidies have a key role in determining project performance (Zhao et al., 2016; He and Lin, 2019).

Given the above, the impact of environmental regulations on the PPP WTE incineration industry, especially on the government subsidies of incinerators, is a problem that deserves much attention. And importantly, as mentioned earlier, the impact of environmental regulations on industry performance involves three different theoretical perspectives with abundant research, which can provide a reference in revealing the underlying mechanism behind environmental regulation and the government subsides of PPP WTE incineration projects.

3 Methodology

A multiple regression model based on panel data is used to investigate the influence of different stringent environmental regulations on government subsidies of PPP WTE incineration projects and their underlying mechanisms. Panel data is used as it can not only show information and dynamic changes, but also reveal differences between subjects, which is beneficial to describe subject behaviors (e.g., Balestra and Nerlove, 1966; Mundalk, 1978).

3.1 Variable selection and measurement

Government subsidies are taken as the dependent variable, while environmental regulation serves as the main independent variable. The research is conducted at the provincial level. Considering data availability and industry heterogeneity, a performance-based indicator is used–the ratio of pollution charge to regional value-added—as the representative variable to define and measure the stringency of environmental regulations. Three typical pollution types of the WTE incineration industry are selected: namely, wastewater, SO_2 (representing waste gas), and solid waste (Olsthoorn et al., 2001; Boyd et al., 2002). Table 2 provides the definitions of the independent variable involved.

To ensure the accuracy of the results, some vital factors which influence the association between environmental regulations and government subsidies of PPP WTE incineration projects need to be controlled for. These include the urbanization rate (UR) and average urban GDP (AGDP), which reflect the level of social/economic development, respectively; and regional technological R&D (RD), representing regional innovation ability. Those three key factors are selected based on Stavropoulos et al. (2018), Zhang et al. (2017), and Piao and Lin. (2020). Table 3 provides the specific definitions of the variables involved.

3.2 Model setting

The square term of environmental regulation comprehensive index is employed to ascertain the presence of a nonlinear relationship between environmental regulation and government subsidies. And the logarithmic form of the variables is helpful to avoid heteroscedasticity and linearity problems. The model is

$$\ln GSI = C + \ln ER_{it} + \ln \overset{2}{ER}_{it} + \ln UR_{it} + \ln AGDP_{it} + \ln RD_{it} + \varepsilon \quad (1)$$

where i and t signify a city (i = Hangzhou, . . . , xxx) and the year (t = 1, 2, . . . , xxx), respectively. C is a constant term and ε is the error term. lnGSI represents the logarithm of the government subsides of PPP WTE incineration projects. lnUR represents the logarithm of

TABLE 3 Variable definitions.

Type	Variable	Name	Definition
Dependent variable	GSI	Government subsides of PPP WTE incineration projects	The tender price of PPP WTE incineration projects
Independent variable	ER	Comprehensive environmental regulation indicator (%)	Measured in Table 2
Control variable	UR	Urbanization rate	Urbanization rate = urban population/total population
	AGDP	GDP *per capita*	GDP *per capita* = GDP/number of people
	RD	Proportion of R&D expenditure to urban GDP	Proportion of R&D expenditure to urban GDP = R&D expenditure/GDP

the comprehensive environmental regulation indicator. lnAGDP represents the logarithm of the urbanization rate. lnRD represents the logarithm of the proportion of R&D expenditure to urban GDP.

3.3 Sample selection and data collection

By the end of 2017, there were 286 PPP WTE incineration plants distributed in more than 180 cities in China (Lee et al., 2020). In order to ensure the study's accuracy and credibility, the samples were screened according to the following inclusion criteria:

(1) Before 2013, the benchmark price of electricity sold by incinerators was not standardized, which may affect the government subsidies of incinerators (Arias and Beers, 2013). Thus, to improve the accuracy of this study, the WTE incinerators established before 2013 were excluded.
(2) To obtain a complete set of urban pollutant emissions data, WTE incinerators that lack official city-scale pollutant emission data in provinces (autonomous regions) such as Yili and Hotan in Xinjiang are excluded.
(3) In China, especially in some large cities or municipalities, a minority of WTE incinerators (such as the Hangzhou Jiufeng PPP WTE Incineration Plant) were built in accordance with European standards instead of national standard (Liu et al., 2019). In such cases, stricter emission standards are usually adopted, which cannot accurately reflect the national emission standards. Thus, WTE incinerators that do not match the requirement of local regional environmental regulation are excluded.
(4) In China, competition in the WTE incinerator market is becoming increasingly fierce, and few investors enter the PPP WTE incinerator market with a low-price competition strategy (Song et al., 2017). For example, in 2017, the Jiangsu Gaoyou PPP WTE incinerator's tender price was CNY 26.5/t, which is far lower than its actual cost price. For the accuracy of this study, WTE incinerators with abnormally low data are therefore omitted, together with those with very low government subsidies of less than CNY 30/t.

According to these standards, a total of 81 PPP WTE incineration projects established in 66 cities in China from 2013 to 2017 are taken to be a valid sample. The panel data at the regional urbanization level, regional economic, and social development level are derived from the China Statistical Yearbook (2013–2017), and the statistical bulletin of national economic and social development in various regions. The environmental regulation data are derived from the China Environmental Statistics Yearbook (2013–2017) and National Bulletin of environmental statistics. The data related to the government subsidies of PPP WTE incineration projects are primarily derived from the China Public Private Partnerships Center, E20 Environment Platform, and E20 Institute of Environment Industry. Data that cannot be obtained through the above channels are usually obtained by telephone contact with specific incinerators.

TABLE 4 Variable descriptive statistics.

Variable	Mean	Std. Dev	Min	Max
GSI	4.18	0.27	3.43	4.74
WW	0.97	0.88	−1.11	2.87
WG	−6.73	1.05	−10.23	−4.25
SW	4.46	0.24	3.03	4.61
UR	4.01	0.29	3.34	4.55
AGDP	10.96	0.55	9.73	11.94
RD	−1.08	0.89	−2.63	1.75

3.4 Data processing

The data (see Supplementary Material) are processed in three steps. First, stationery checking is carried out to analyze whether the whole data meets the panel data standard. Second, the endogenous problem is tested, excluding the endogenous problems of the core explanatory variables and the explained variables. Third, the multiple linear regression model, widely used in sociological research, is used to verify the impact mechanism of environmental regulation on the government subsidies. Fourth, a robustness analysis is conducted to test the reliability of the results of the multiple linear regression model and to verify the influence of environmental regulation on the PPP WTE incineration industries.

4 Results

4.1 Descriptive statistics of variables

Table 4 provides the descriptive statistics of the variables, showing there are significant differences between the minimum

TABLE 5 Test results of the stationarity analysis.

Variable	Intercept term		Intercept term and trend term		No intercept term and no trend term	
	LLC	PP	LLC	PP	LLC	PP
	Same root hypothesis	Hetero root hypothesis	Same root hypothesis	Hetero root hypothesis	Same root hypothesis	Hetero root hypothesis
lnGSI	−9.473	18.421	−9.934	18.421	−10.646	263.391
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnER	−8.647	18.421	−9.330	18.421	−9.369	263.391
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln^2ER	−7.635	18.421	−7.974	18.421	−9.383	263.391
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnWW	−10.135	18.421	−10.600	18.421	−11.881	263.391
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnWG	−6.375	18.421	−6.325	18.421	−9.835	263.391
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnSW	−4.459	18.421	−4.123	18.421	−8.878	263.391
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnUR	−10.070	18.421	−10.702	18.421	−12.060	263.391
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnAGDP	15.147	18.421	15.003	18.421	−6.844	263.391
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnRD	−4.435	18.421	−4.177	18.421	−8.426	263.391
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

Note: the values in brackets indicate the corresponding estimated *p*-value.

and maximum of all variables, as expected, therefore, there are sizeable differences in the indicators between different projects.

4.2 Endogenous analysis

In this study, the causal relationship between environmental regulation and government subsidies could potentially be bidirectional, thus requiring a further examination of endogeneity. In endogenous testing, other control variables are treated as exogenous. Accordingly, Hausman test was conducted by using Stata17 software to check the endogeneity in the model.

In particular, three instrumental variables (Martens et al., 2006) were identified: air circulation coefficient, PM2.5 index, and urban wastewater discharge. If the null hypothesis is rejected (*p*-value <0.1), it suggests that environmental regulation is an endogenous explanatory variable. Conversely, if the null hypothesis is not rejected, it indicates the absence of endogeneity issues (Chetty et al., 2014). The results of the Hausman test showed the *p*-value of 0.2171, which is greater than 0.1. Therefore, it can be concluded that ER is not an endogenous variable, and there is no endogeneity in the model.

In addition, it is necessary to conduct an overidentification test and a weak instrument test on the three instrumental variables to examine their validity and reliability. In the overidentification test, if the *p*-value corresponding to the Sargan-Basman statistic is greater than 0.05, it indicates that all instrumental variables are exogenous and effective. Otherwise, they are considered ineffective. In this study, the results of over identification test reveals that the Sargan (score) chi2 (2) = 1.35774 (p = 0.5072), with a *p*-value greater than 0.05, indicating that the instrumental variables are effective.

In the weak instrument test, if the probability value of the statistic obtained after using the "estat firststage" command is less than 0.05, it suggests that the instruments are appropriate. Otherwise, there may have the problem of weak instruments (Hahn et al., 2011). As a result, Shea's partial R-squared is 0.0269, which is less than 0.05, suggesting that the instrumental variables are appropriate for the model.

4.3 Stationarity analysis

Table 5 summarizes the unit root test results of panel data stationery analysis, showing all variables to be highly significant irrespective of the inclusion of the intercept term, intercept term and trend term, or no intercept term and no trend term. The sample

TABLE 6 Results of the multiple regression analyses.

Variables	(1) GSI	(2) GSI
lnER	0.466*	0.988*
	(0.124)	(0.226)
ln^2ER		−0.656*
		(0.415)
lnUR	0.377*	0.500*
	(0.098)	(0.116)
lnAGDP	0.079	0.034
	(0.037)	(0.038)
lnRD	−0.386*	−0.541*
	(0.025)	(0.032)
Constant	−0.494	0.193
	(0.218)	(0.320)

Note: *, **, *** indicates significance at the 5%, 1% and 10% level, respectively; the values in brackets indicates the standard deviation.

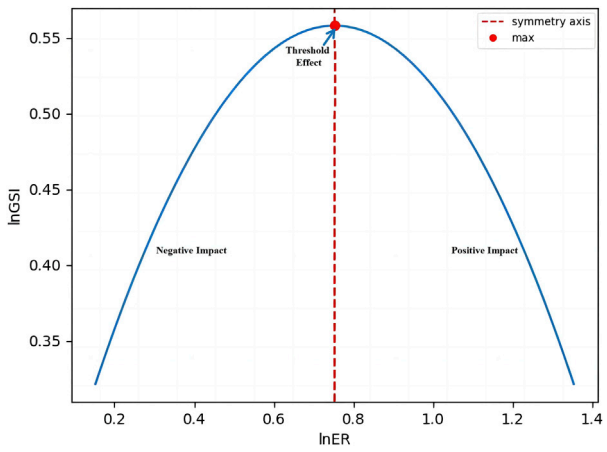


FIGURE 1
Schematic diagram of the model results.

data, therefore, meets the requirements for panel data regression analysis.

4.4 Multiple regression analysis

Table 6 presents the results of the linear and non-linear multiple regression analyses, showing that the linear coefficient of environmental regulation is 0.466, indicating that environmental regulation has a significant positive effect on the government subsidies, i.e., the stricter the environmental regulation, the higher the government subsidies.

Table 6 also shows that the primary term coefficient of environmental regulation is positive. In contrast, the quadratic term coefficient is negative, both of which are significant at the 5% level, indicating the impact of environmental regulation on government subsidies is not a simple linear relationship, but an "inverted-U" relationship, as shown in Figure 1.

TABLE 7 Robustness test based on multiple control variables.

Variables	(1) GSI	(2) GSI
lnER	0.302*	0.157*
	(0.172)	(0.093)
ln^2ER		−0.423*
		(0.153)
lnUR	0.386*	0.333*
	(0.103)	(0.104)
lnAGDP	0.064	0.056
	(0.036)	(0.035)
lnRD	−0.334*	−0.295*
	(0.028)	(0.029)
lnDC	0.019	0.013
	(0.088)	(0.087)
lnEDU	−0.340*	−0.335*
	(0.100)	(0.099)
Constant	0.608	0.533
	(0.235)	(0.236)

4.5 Robustness test

While many indicators can be used to measure the economic and social development of a region, only one is used here as a control variable. It is necessary, therefore, to verify the validity and reliability of

the empirical analysis results by a robustness test. This is done by adding the control variables of incineration plant size and regional educational development (Zhou et al., 2017; Liu et al., 2018). These are proxied by the daily treatment capacity of the projects (DC) and the number of college students per 10,000 residents (EDU), respectively.

Table 7 shows the test results, indicating that the primary coefficient of environmental regulation is 0.157 and secondary coefficient is −0.423, both of which are significant at the 5% level. This demonstrates the relationship between environmental regulation and government subsidies to be still an "inverted-U" shape. The robustness test results of control variables UR, AGDP, and RD are also consistent with those in Table 6, and measurement results are therefore reliable.

5 Discussion

The multiple regression analysis results show that environmental regulation and government subsidies of PPP WTE incineration projects have an "inverted-U"-shaped relationship: environmental regulation first has a negative impact on government subsidies, that subsequently turns into a positive impact. When environmental regulation is lax, the projects' government subsidies have an upward trend; when environmental regulations are stringent, there is a downward trend. These results are consistent with the uncertainty hypothesis that environmental regulation has an uncertain impact on industry performance (Tan et al., 2017; Yuan and Xiang, 2018).

As described, the government subsidies of PPP WTE incineration projects can be regarded as a kind of "product/service price" paid by the local government (buyer), which is determined by market competition and bidding to attract the private sector (provider) to invest, construct, and operate the incineration plant. In general, from an industrial market perspective, high government subsides of projects means that the industry has insufficient ability to offer a superior "product", reflecting the industry's low performance level (Wang and Shen, 2016). Thus, due to the significant role of government subsides of PPP projects in reflecting the WTE incineration industry, the "inverted-U"-shaped relationship between environmental regulation and government subsidies can be explained as follows.

The regression results show that environmental regulations firstly have a negative impact on the government subsidies: this is because, when environmental regulations are lax, most incineration plants are insufficiently motivated towards technological innovation and emission reduction due to the reasons given by Porter (Mbanyele and Wang, 2022). This leads to the industry weakening its competition, resulting in a high "product price" - the government subsidies of projects. As the further strengthening of environmental regulations, there is a turning point where environmental regulations no longer has a negative impact on government subsidies, which has become a threshold effect. Subsequently, the decreasing trend suggests that increasing environmental regulation after the turning point reduces the amount of government subsidies. According to Stavropoulos et al. (2018), strict environmental regulation can downsize the capital stock and modernize the machines, leading to an average increase in productivity and, ultimately, result in the reduction in the "product price".

Indeed, the threshold effect in this study has a deeper reason. Be specific, China is currently undergoing a transition towards a novel form of industrialization, which is characterized by a win-win balance between economic advancement and environmental protection (Wang and Feng, 2021). The development of industries is normally considered in the formulation of environmental regulation. The famous concept of "cost effect" pointed out that during the initial stage of industrial development, environmental laws and regulations tend to raise the cost of pollution control for enterprises (Song et al., 2021). Consequently, the government may control energy-saving and emission-reduction measures to ensure the sustainable development of the environment (Lin and Zhu, 2019). Even in the absence of significant technological innovations, pollution-intensive enterprises inevitably incur certain pollution control costs. As environmental regulation becomes more stringent, a turning point is reached where the high cost of pollution control starts to impede normal project operations (Porter and Linde, 1995). At this time, some enterprises are compelled to invest in technological innovation to improve project operational efficiency, thereby reducing pollution control costs (Yin et al., 2022). The arrival of the turning point hinges on a project's capacity to withstand increasingly stringent environmental regulations. Enterprises with weaker resistance will encounter the turning point earlier, while those with stronger resistance will delay the arrival (Zeng et al., 2022). However, given the continual escalation of environment regulation, the arrival of the turning point is inevitable.

At present, due to China's unique circumstances, WTE incineration projects stand as the primary waste treatment method. According to our research findings, as the environmental regulations become more stringent and a threshold effect is reached, these enterprises engage in technological innovation within their projects. This innovation serves to lower the costs associated with pollution control, ultimately enabling businesses to attain greater economic returns. However, the existing incineration technologies still come with certain environmental costs, including contributions to the greenhouse effect and air pollution (Tait et al., 2020; Cudjoe and Acquah, 2021). As these environmental costs contribute to mount, health-related expenses also rise. Therefore, in line with the government's implementation of environmental regulations, it is imperative for relevant authorities to reasonably adjust the intensity of subsidies for corporate innovation and guide businesses towards more environmentally innovative development. Also, enterprises should increase technological innovation and adopt eco-friendlier waste treatment methods. Promising options include drawing upon international experiences in anaerobic digestion (Anukam et al., 2019) and aerobic composting (Tran et al., 2021) technologies. The aim should be to achieve a balance between environmental and economic benefits.

6 Conclusion and policy recommendations

Taking the allocation of 81 PPP WTE incineration projects in 66 cities in China as the unit of research, this study aimed to explore the mechanism behind the impact of environmental regulations on the subsidies of PPP WTE incineration projects using multiple regression models. The results show that the relationship between environmental regulation and the subsidies is an "inverted-U″ shape. With the strengthening of environmental

regulation, the subsidies tend to first rise and then fall. Furthermore, before crossing the inflection point, the higher the intensity of environmental regulation, the higher the government subsidies; when the regulation intensity reaches a high level or exceeds a certain threshold value, continuing to increase the environmental regulation intensity promotes the project's technological innovation, and then reduces the subsidies. This conclusion is consistent with the uncertainty hypothesis in the related theories of environmental regulation; that is, the effect of environmental regulation on the government subsidies is non-linear.

These findings suggest the following environmental regulation policy implications.

(1) In the stage of positive impact, the government needs to centrally manage resources, and hence guide and integrate the advantages of regional companies to strive to maximize operational efficiency (Jones et al., 2010; Zhao et al., 2015). The PPP WTE incinerators need to further adopt advanced management methods and update technology and equipment to achieve sustainable long-term development.
(2) In the negative impact stage, the government should support and guide the WTE incineration industry with well-designed policies. Additionally, through the establishment of a good order of the market and using scientific administrative methods to reduce the environmental cost of companies, the government can accelerate technology innovation in companies, especially newly started incineration plants in the central and western regions of China, so as to help them quickly pass through the negative impact stage of environmental regulation (Zhu et al., 2014; Yasmeen et al., 2020). On the other hand, the PPP WTE incinerators need to enhance their anti-risk ability. It is meaningful for incinerators, whether large, medium, or small in size, to give full play to their own advantages, as well as the adoption of diversified development strategies in combination with multi-field advantages.

This study is beneficial for both the public and private sectors in fully understanding the impact of environmental regulation on the WTE incineration industry. Furthermore, it proposes strategic suggestions for companies to meet the change of environmental regulation intensity, and also provides a reference for the government to guide the development of regional companies. Additionally, it accelerates the sustainable development of the WTE incineration industry and establishes a foundation for further associated scientific research in China. Therefore, clarifying the mechanism influencing environmental regulation on the government subsidies of PPP WTE incineration projects will make considerable contribution to the industry's sustained and healthy development.

Although the effect of environmental regulation on the government subsidies is verified empirically, only projects established during 2013–2017 were selected, and thus more cases need to be studied in the future. Moreover, more studies are required in order to explore other control variables involved in the issues affecting government subsidies of the PPP WTE incineration industries.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

YS: Formal Analysis, Software, Writing–original draft. MX: Data curation, Investigation, Resources, Writing–original draft. CC: Writing–review and editing. BX: Software, Visualization, Writing–review and editing. MS: Methodology, Supervision, Validation, Writing–review and editing. MM: Conceptualization, Validation, Writing–review and editing. YL: Conceptualization, Funding acquisition, Methodology, Project administration, Writing–original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1288851/full#supplementary-material

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The complexity of environmental policy implementation in China: a set-theoretic approach to environmental monitoring policy dynamics

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The implementation of environmental monitoring policies is of great significance in reducing pollution and improving the ecological environment. This study looks at three dimensions of Sabatier's policy environment framework: the tractability of the problem, the ability of the statute to structure implementation, and non-statutory variables, explores in detail the complex configuration of technology availability, change required, financial resources, implementing officials, public support, and socio economic conditions. The results based on data from 30 provinces in China identify four different combinations of conditions that match "Opinions on Deepening the Reform of Environmental Monitoring and Improving the Quality of Environmental Monitoring Data" environmental monitoring policy implementation: "priority governance" means that the change required is the most important variable in high-pollution provinces, "money talks" suggests that financial resources are a more important condition in north-western provinces, "coordinated implementation" is associated with non-statutory variables such as public support and socio-economic conditions being neither sufficient nor necessary conditions; and when both the ability of the statute and nonstatutory variables were identified as necessary conditions, as in the capital city, this is termed the "comprehensive strategy".

KEYWORDS

public policy, environmental monitoring policy implementation, fs-QCA, policy implementation process, configuration combination

1 Introduction

In recent years, China's rapid economic development and environmental pollution problems have become increasingly prominent, and the implementation of environmental monitoring policies is of great significance in reducing pollution and improving the ecological environment. The Chinese government has issued a series of environmental protection policies and regulations, of which environmental monitoring policy is an important part, and its implementation is directly related to the implementation of environmental protection policies. In addition, the continuous progress of environmental monitoring technology and the accumulation of environmental monitoring data provide more possibilities and challenges for the implementation of

environmental monitoring policies. Not only that, the international community is increasingly concerned about environmental issues, and the study of China's environmental monitoring policy implementation also needs to consider the trends and requirements of international environmental governance. Therefore, an in-depth study on the implementation of China's environmental monitoring policy will help improve the environmental monitoring policy system, enhance the effectiveness of the implementation of environmental monitoring policy, and promote the practical advancement of environmental protection.

Studying environmental monitoring policy implementation and evaluating its determinants is an important topic in public policy research (Swanson et al., 2001; Vesterager et al., 2016; Howes et al., 2017; Zhang and Yao, 2018). Sabatier and Mazmanian (1980) proposed a policy implementation framework by examining the stages of different factors and the achievement of statutory objectives. A series of studies followed their original research and studied the effects of factors such as stakeholder participation, economic conditions, technology and human resources (Challies et al., 2017; Klaster et al., 2017; Teodoro et al., 2018). Another strand of the literature studied implementation strategies and focussed particularly on the influence of different conditions (Ingram, 1990; Matland, 1995; Li et al., 2023). A number of variables such as interest group pressure (Lundin, 2007; Sharp et al., 2011), central government support (Zhan et al., 2014), and implementing officials (Sabatier, 1986) have been analysed.

The majority of recent studies have used case analysis to indicate whether the framework in question has been successfully applied (Sabatier, 1986). A key problem with much of the literature on environmental monitoring policy implementation is that the conclusions drawn from case studies are inspiring but have limited generalizability (Wang, 2016; Wang and Zhou, 2022). Second, conventional statistical analysis is limited when attempting to test the complex causal relations among explanatory variables (Fiss, 2011). Although scholars have begun to focus on individual policy implementation variables (Tuokuu et al., 2018), more research is needed to cover the effects of various combinations of conditions. Third, most empirical research on the variables involved in policy implementation has been based on the US or European countries, and we know little about whether this framework is applicable to developing countries such as China.

With the continuous promotion of ecological civilisation construction in various countries, the breadth and depth of the implementation of various types of environmental policies are continuously extended, and in this process, the factors affecting the implementation of environmental policies can not be ignored more and more. The policy implementation framework based on Sabatier scholar has been widely applied in many fields such as agriculture, education, medical care, laws and regulations. For example, Yang and Huang (2022) explored the historical evolution of rural teacher supplementation policy based on the Sabatier policy implementation framework, and Foley, 2015 scholar explored the practice differentiation of the implementation of poverty subsidy policy in township secondary schools based on the Sabatier framework model in the context of education poverty alleviation (2015). In the field of agriculture, Montefrio and Sin., 2021 explored the effectiveness of the implementation of the policy based on the practice of facility-based agriculture policy on the farms and the landing situation, for example, (2021). In addition, Li et al., 2022 scholars explored the influencing factors of poverty alleviation policy implementation in poverty-stricken areas based on the policy implementation framework (2022); in the medical field, Gauthier-Beaupré et al., 2023 explored the evolution of medical and health policies based on the evolution and development of Sabatier's framework (2022). Comprehensively, it is not difficult to find that the Sabatier policy implementation framework is a good guide for scholars to understand the influencing factors affecting policy implementation. However, with the passage of time and the change of application scenarios, it is not yet known whether the Sabatier policy implementation framework is suitable for exploring the effectiveness of environmental monitoring policy implementation in the Chinese context. Most of the existing studies have been conducted on the basis of the original framework, and there is no answer to the question of whether there are interactions between the influencing factors and whether their combination and configuration have an impact on policy implementation.

Based on this, this article attempts to further the study on environmental monitoring policy implementation by developing configuration theories for policy implementation. We use a set-theoretic approach. Fuzzy set qualitative comparative analysis (fs-QCA) enables us to address equifinality, conjunctural causation, and asymmetric relations among explanatory variables (Meuer and Rupietta, 2017). In addition, this article is based on the cases of 30 Chinese provinces in 2016, which provides an opportunity to test the factors and framework developed for analysing Western societies.

2 Theoretical framework

Although an enormous amount of research has been conducted on policy implementation, there are few synthetic theories that integrate most of the approaches. The top-down and bottom-up perspectives of policy implementation offer different explanations for implementation strategies. Scholars examining commitment-oriented hypotheses scholars have sought to identify the best way to move from a policy proposal to successful implementation (DeLeon and DeLeon, 2002). The top-down approach emphasizes centrally defined policy intentions and their hierarchical execution (Treib, 2006). Sabatier and Mazmanian (1980) performed a pioneering study on public policy implementation and developed a conceptual framework that consists of the tractability of the problem, the ability of the statute to structure implementation, and non-statutory variables. Sabatier (1986) furthered this research by explaining that each of the policy stages can affect subsequent stages, and he then proposed the six sufficient and generally necessary conditions for effective policy implementation: clear objectives, adequate theory, legal structure, effective implementing officials,

political and public support and stable socio-economic conditions (Wang et al., 2022).

In contrast, the bottom-up perspective contends that street-level bureaucrats represent the key factor in monitoring policy implementation (Hjern, 1982). By arguing that the top-down perspective research focuses mainly on rigorous models but has a misplaced focus, the bottom-up perspective assumes that environmental monitoring policy implementation should combine freedom and capacity for action (Sevä and Jagers, 2013). The main difference between the two perspectives is whether policy implementation needs to be included in policy formulation (DeLeon and DeLeon, 2002). In line with previous policy implementation research, in this article, we define environmental monitoring policy implementation as environmental monitoring laws being translated into implemented programs.

The reasons for selecting the Sabatier and Mazmanian (1980) policy implementation process as the major theoretical framework in this article were as follows. Firstly, an increasing number of studies have found that Chinese policies are generally formulated by the central government, while local officials simply implement the policy (Manion, 1991; Zhou, 2010; 2017), and the Communist Party of China always provides overall leadership and coordinates the efforts of all involved. Additionally, in such a governing system, the top-down perspective will help us to illustrate the factors involved in the policy implementation process. Secondly, the framework analyses the interactions among different factors throughout the policy implementation process, which is the focus of the present article. By identifying the complex causal relations involved in environmental monitoring policy implementation, this framework provides the basic foundation for this study and offers opportunities for further modifications.

While Sabatier and Mazmanian (1980) illustrated in considerable detail why the tractability of the problem, the ability of the statute to structure implementation and non-statutory variables affect policy implementation, this article outlines these aspects only briefly and instead focuses on explaining how the policy implementation framework differs across the three stages. To further develop the theory of environmental monitoring policy implementation, I provide further details on these three aspects with respect to the Chinese cultural context, as explained in the following sections. Firstly, I suggest different explanations for the six necessary variables for monitoring policy implementation. Secondly and more importantly, I introduce a framework based on set theory that accounts for the causal complexity of environmental monitoring policy implementation.

2.1 Tractability of the problem

The tractability of the problem is probably the most commonly studied variable in the public policy implementation literature. The tractability of the problem consists of the aspects of problems affecting the ability of policy implementers to achieve the policy's objectives and concerns the inherent nature of the problem involved (Lester and Bowman, 1989). The tractability of the issue refers to the explicitness of the issue with respect to the policy, which is addressed in statutory objectives (Ma, 2008). It concerns social problems instead of governmental programs or governments *per se*, and social problems can affect the ability to implement an environmental policy with respect to an individual variable or in the aggregate. The summary index of tractability includes four variables, namely, technical theory and technology, target group behaviour, the percentage of the target group, and the extent of behavioural change required (Sabatier and Mazmanian, 1980). The framework employed in this article holds that factors affecting the ability to implement policy can be divided into two aspects. The first is technology availability, which concerns developing the necessary technology to enable target groups to achieve the desired objectives. The second aspect is the extent of behavioural change required.

2.2 Technology availability

The typical assumption in the literature is that some time is required to develop the necessary level of technology availability to implement environmental policy. For example, being able to reduce in sulphur emissions is contingent upon having the technology needed for removing sulphur from the emissions of power plants. Technical problems could lead to implementation failure, such as mechanical malfunctions (Matland, 1995; Zhang et al., 2022). Firms in China that pass compulsory cleaner production audits and evaluations have demonstrated their ability to overcome technological difficulties. A study on the effect of technology availability in the context of hazardous waste control demonstrated that effective implementation is based on finding reliable and applicable technology (Lester and Bowman, 1989; Zeb et al., 2023). We therefore expect that in the absence of the specific technologies required, the target group's behaviour will not achieve the program objectives. Firms that pass compulsory cleaner production audits and evaluations demonstrate technology availability because these companies have the ability to overcome technological difficulties.

2.3 Change required

The change required represents how extensive the amount of behavioural change required by target groups is. In this context, "micro-issues" refer to rare situations and imply only negligible costs, while "macro issues" related to frequently occurring situations and impose substantial requirements on the target group (Thomann et al., 2019). The goal of reducing the number of heavy-pollution days provides an example of the visibility of and the importance attached to statutory objectives. The greater the number of heavy-pollution days, the more difficult implementing such a policy will be (Sabatier and Mazmanian, 1980); the basic hypothesis here, of course, is that the greater the number of heavy-pollution days in a province, the more substantial the behavioural change necessary to reduce them will be. However, some polices that demand substantial behavioural change seem to be implemented quite smoothly

(O'Toole, 1986). In such a case, the "noncompliance delay effect" would have a greater impact on policy implementation than the degree of behavioural change required (Durant, 1984).

2.4 Ability of the statute to structure implementation

According to the Sabatier and Mazmanian (1980) policy implementation process framework, the ability of the statute to structure implementation is the fundamental category in determining the success of the policy implementation. The ability of a statute to affect policy implementation includes the extent to which different variables structure the implementation process, such as the financial resources available to the implementing agency and the implementing officials being committed to the statutory objectives.

2.5 Financial resources

Financial resources concern the amount of funding local environmental protection boards (EPBs) receive from local governments or superior agencies. Obviously, money is important for any program. For example, money is important to purchase environmental monitoring equipment and hire the staff involved in the implementation process, technical analysis, program administration and monitoring. Research has shown that cutbacks in environmental expenditures have negative implications for hazardous waste control (Lester, 1986). It is necessary to have a threshold level of funding available to achieve policy objectives, and traditionally, the operationalization of financial resources is measured by the total financing the government provides to the provinces (McFarlane, 1989). To measure the financial resources invested in environmental policy, this study considers environmental investment needed in an area divided by gross domestic product (GDP). In the Chinese context, investment in environmental pollution treatment is an important way for local EPBs to obtain funding. I also include a financial resource among the statutory variables.

2.6 Implementing officials

A top-down perspective suggests that the implementing agencies and officials being committed to statutory objectives is important for achieving these policy targets. The bottom-up perspective contends that identifying the micro-level contextual factors at the local level is also important for policy outcomes (Matland, 1995). The implementing officials represent the micro-level that directly affects target groups. Street-level bureaucrats, first-line managers, and middle managers are the three main groups involved in implementation (Gassner and Gofen, 2018).

In other words, the actors involved in the policy implementation process must understand the policy to understand how to implement it. Implementing officials need to translate formal policy decisions into daily tasks before being able to directly deliver multiple policies (Gassner and Gofen, 2018). In the present work, the implementing officials variable measures the extent to which the policy implementors understand the statutory objectives, which requires solid legal and technical knowledge. In most environmental policy programs, for example, the target groups are not particularly familiar with legal issues and do not generally have a specific target to pursue in their activities. By contrast, implementing officials are intermediary agents that guide firms and help them to translate legislative goals into actual action. Implementing officials need to interact with the target groups, and a number of programs require officials who are familiar with and confident in the statutory objectives. Implementing officials being familiar with environmental policy and having the related skills are critical, and the effort needed to issue an environmental monitoring certificate is considerable.

2.7 Non-statutory variables

Given the assumption that local EPBs attempt to achieve certain goals, we should not only focus on the statutory variables but also consider the non-statutory variables. In other words, variables exogenous to the policy implementation process can determine the successful implementation of public policy. According to Sabatier and Mazmanian (1980), some important variables influence policy implementation, including the relevant socio-economic conditions, media attention, public support, business groups' attitudes, and political support. There are at least two important processes that contribute to the dynamism inherent in implementation. First, successful program implementation demands political support and cooperation or acceptance by many people. Second, the effect of changes in socio-economic and technological conditions influence the reservoir of support for objectives among stakeholders. This article focuses on public support and socio-economic conditions as aspects of the non-statutory variables.

2.8 Public support

There are three types of general public support that can influence policy implementation: public opinion, general constituents, and support for particular policy positions (Sabatier and Mazmanian, 1980). The general public can influence policy implementation because public opinion can affect the political agenda (Burstein, 2003). Greater public support for EU environmental policy played a large part in determining the outcomes of political issues in Europe (Jordan, 1999). Our research focuses on public opinion and its interaction with local EPBs. The official telephone hotline and complaint letters from citizens could easily drive the policy implementation team's monitoring priorities. Moreover, increased citizen complaints and media exposure prompt accelerated policy implementation to avoid criticism (Zhan et al., 2014). General public support can influence environmental monitoring policy implementation through the reporting of polluting activities, including complaint letters and reports through social network reporting platforms. It is easier for citizens to report polluting activities through the WeChat messages

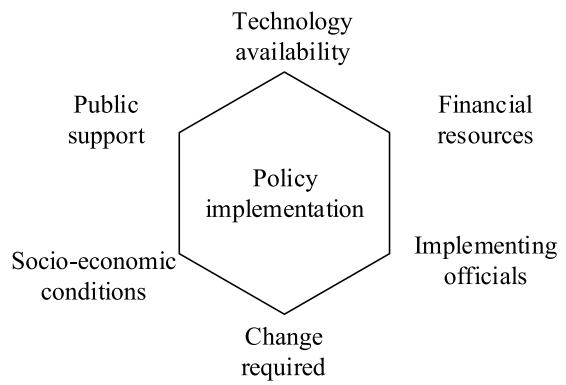


FIGURE 1
Research frame diagram. This is a figure. Schemes follow the same formatting.

forwarded to the responsible local EPBs. The support from interest groups and political facilitate "administrative implementation", and the Chinese general public increased its support for environmental monitoring policy implementation from 2000 to 2006 (Zhan et al., 2014).

2.9 Socio-economic conditions

Obviously, socio-economic conditions can substantially affect environmental monitoring policy implementation since some local governmental leaders care more about industrial development or economic growth. Given the weak authority of local environmental officials in China, it is difficult to implement environmental policy when local governmental leaders care more about economic growth (Lieberthal, 1997). When a local government's top priority is economic development, it will likely be reluctant to give enough support for local EPBs, as economic development targets sometimes conflict with environmental protection (Zhan et al., 2014). In China, local governments have different policy targets because of differences in socio-economic conditions across regions, which may lack the motivation to fully implement environmental policy (O'Brien and Li, 2017). GDP (total or *per capita*) is one of the most popular performance indicators used in regional rankings (Xu, 2011).

2.10 The causal complexity of environmental monitoring policy implementation

As Sabatier and Mazmanian (1980) illustrate in their detailed explanations of the three aspects, the combined effects of the tractability of the problem, the ability of the statute to structure implementation and non-statutory variables are decisive for the policy implementation. In other words, environmental monitoring policy implementation is affected by the different combinations of these three aspects. Sabatier (1986) explains that each of stage can affect subsequent stages. Based on this framework for the policy implementation process, it has been suggested that identifying these variables is a useful approach to analysing environmental monitoring policy implementation. This results in five stages of the implementation process that are affected by the specific variables. However, I argue that the skeletal flow diagram does not fully capture the causal complexity of environmental monitoring policy implementation, which is why I develop a more elaborated conceptual framework (see Figure 1).

This framework of environmental monitoring policy implementation is rooted in set theory, which implies that, according to set theory, policy implementation consists of six variables: technology availability, change required, financial resources, implementing officials, public support and socio-economic conditions (Sabatier and Mazmanian, 1980). To explain these six core variables in set theory, I refer to the example of studying environmental monitoring policy implementation.

First, policy implementation is not simply the opposite of failed implementation. "Policy implementation is constrained by changing organizational environments and varied local settings in the real world" (Zhan et al., 2014), which implies asymmetric causal relations between the variables and environmental monitoring policy implementation. This is why the framework is based on the causal asymmetry assumption: the reason that environmental monitoring policy implementation succeeds is not simply the opposite of what explains implementation failure.

Second, it is easier for us to examine the different variables and examine how their interplay affects environmental monitoring policy implementation via the framework. That policy implementation emerges from the intersection of different variables as appropriate preconditions is the basic idea of conjunctural causation (Ragin, 2014). In contrast to previous research, which classifies policy implementation by focusing on the full range of implementation activities (such as the different stages of the policy implementation process), the combinations of conditions of the framework conjointly cause environmental monitoring policy implementation. While the initial framework consisting of the three aspects has already been tested with respect to conjunctural causation, such attempts have been limited to individual variables, by contrast, I attempt to identify the diffident combinations of technology availability, change required, financial resources, implementing officials, public support and socio-economic conditions through a new framework. Based on the above theoretical framework, environmental monitoring policy implementation can reflect a variety of combinations of various types of variables involved and not be limited to individual ones. Furthermore, the framework assumes that the relationships between environmental monitoring policy implementation and the six variables are diverse instead of simply having an interactive effect, as argued in the initial framework. In contrast to the stage-based analysis, where three categories of variables affect the different stages of the policy implementation, the different combinations of the six variables considered here are used in the empirical investigation of environmental monitoring policy implementation.

Third, this article attempts to reveal new explanations for environmental monitoring policy implementation based on the new framework. The empirical part of this article attempts to explain reality and applies the framework to identify which combinations of variables ensure environmental monitoring

policy implementation. Moreover, the framework is also a toolbox of policy implementation strategies that local EPBs can use when determining the set of factors they should consider. In the real world, different provinces apply different sets of strategies to implement policy, which is why I attempt to identify combinations of variables that overlap. The set-theoretic perspective adopted in this analysis unravels the causal complexity of the different combinations of variables and thereby adds value by providing new and more useful strategies for local government agencies.

3 Materials and methods

The theoretical framework for environmental monitoring policy implementation developed in this article is based on configurational theory, which argues strongly for breaking the linear paradigm (Fiss, 2007). Similar to research on the best configurations of human resource management (Huselid, 1995; MacDuffie, 1995), this article applies fs-QCA to analyse environmental monitoring policy implementation. By using Boolean algebra and finding different combinations of variables, fs-QCA could explain the key terms and provides causal complexity (Fiss, 2007; Wang et al., 2023).

This method was chosen because it is one of the most feasible ways to examine the combined effects of given variables on environmental monitoring policy implementation. The traditional linear regression model examines the variation in a single variable in isolation (Ragin and Rubinson, 2009); by contrast, fs-QCA represents a useful alternative to test asymmetric causal relations. A set-theoretic approach illustrates which different configurations of six variables, as shown in the framework, lead to environmental monitoring policy implementation. The different combinations of the six variables are called configurations (Fiss, 2011).

In the initial state of the process, the key feature of fs-QCA research needs calibration. The analysis of identifying thresholds is a semi-empirical process that meaningfully represents differences in degree and in kind among cases (Greckhamer et al., 2018). The core of the test of set-subset relationships is a truth table developed using Boolean algebra. The possible configurations of conditions have a truth table with k conditions and 2k rows. Different conditions represent different configurations. For example, some conditions may account for a large proportion of cases, while other configurations may be represented by fewer or no cases. To identify the model's validity, consistency scores report how consistently given observed configurations are related to the outcome (Greckhamer et al., 2018). In other words, high configuration consistency scores mean that the configurational model exhibits strong explanatory power for the outcome.

Generally speaking, quantitative analyses (primary or secondary data) such as traditional regression methods can solve the one-to-one causal relationship between independent variables and dependent variables, but it is difficult to see the complex causal relationship between multiple antecedent conditions in a combined configuration on the dependent variable. The fsQCA method can better solve this kind of combined configuration relationship. fsQCA method treats the research object (dependent variable) as a grouping of conditions, which helps to analyse the causal complexity problems such as multi-causal concurrency, causal asymmetry and equivalence, and it is suitable for this paper to analyse the relationship between technology availability, change required, financial resources, implementing officials, public support, and the complexity of the dependent variable. Resources, implementing officials, public support, and socio-economic conditions are suitable for this paper's study of the complex relationship between necessity and adequacy of technology availability, change required, financial resources, implementing officials, public support, and socio-economic conditions and the implementation of environmental policy.

Essentially, the aim of fs-QCA is to identify the outcome under different configurations of conditions and consists of two procedures: tests of necessity and sufficiency. Necessity means that the outcome cannot be achieved without the specific conditions, while sufficiency concerns whether a condition or conjunctural causation is a subset of the outcome (Fiss, 2011). Necessity analysis should be conducted before sufficiency analysis (Greckhamer et al., 2018). The necessity and sufficiency relations are analysed by using set-theoretic measures of consistency and coverage (Ragin, 2014). Consistency values express "the proportion of cases exhibiting the configuration that exhibit the outcome" (Greckhamer et al., 2018). Coverage measures the "proportion of cases exhibiting the outcome captured by this configuration" (Greckhamer et al., 2018).

3.1 Operationalization

Because environmental policies in China are typically formulated at the Ministry of Ecology and Environment of the People's Republic of China and implemented by local EPBs, the analysis in this article focuses on the province-level government. Measuring policy implementation is challenging, particularly it is a process for different cases. Data on the number of environmental policy monitoring files and executed cases are direct measures obtained from the China Environment Yearbook. However, the yearbook data are limited when considering the different provinces as the cases, as they cover only the year 2016 and lack information on Tibet. By simultaneously applying framework for all variables, the analysis identifies only the six variables in question and does not consider other indicators not included in the framework.

The analysis refers to 30 province-level cases in China in 2016. We selected the sample size on the basis of the six conditional variables. One rationale for choosing the year 2016 is that the Central Committee of the Communist Party of China established an environmental protection supervision committee in that year. The work of local environmental protection bureaus is heavily influenced by central government support (Zhan et al., 2014). The second reason for choosing 2016 was that the latest China Environment Yearbook, which allowed me to access the feasible combinations of different environmental monitoring policy implementation variables was issued in 2017.

The case selection is also guided by the definition of regulatory implementation. In China, there are at least two dimensions for characterizing implementation strategies (Zhan et al., 2014): the degree of formalism and cooperation with other governments. This article classifies environmental monitoring policy implementation as the number of environmental policy monitoring files divided by

TABLE 1 Operationalization of variables.

	Condition	Definition	Operationalization	Source
Implementation	Environmental monitoring (em)	The environmental laws translated into implemented programs	The percentage of the environmental monitoring policy executed divided by the environmental monitoring policy files	China Environment Yearbook 2017
Tractability of the problem	Technology availability (ta)	Technologies that can help the target groups achieve the desired objectives	The number of the compulsory cleaner production audit and evaluation firms	China Environment Yearbook 2017
	Change required (cr)	The amount of behavioural modification required of target groups	The heavy-pollution days of cities at prefecture and above	China Environment Yearbook 2017
Ability of statute	Financial resources (fr)	The amount of funding for local EPBs	The percentage of total investment for environmental pollution treatment divided by regional gross domestic product (GDP)	China Environment Yearbook 2017/China Statistical Yearbook 2016
	Implementing officials (io)	The extent to which the policy implements understand the statutory objectives	The percentage of the number of environmental monitoring staff with the certificate divided by the total staff numbers	China Environment Yearbook 2017
Non-statutory variables	Public support (ps)	Public opinion that affects the political agenda	The number of reported cases from WeChat divided by the region's total population at year-end	China Environment Yearbook 2017/China Statistical Yearbook 2016
	Socio-economic (se)	Economic development	GDP *per capita*	China Statistical Yearbook 2016

the number of executed cases; the percentage so obtained is the indicator for environmental monitoring policy implementation. Very low percentage scores across suggest that a low level of policy implementation ability with respect to the outcome in question and should be considered.

The outcome variable is the environmental monitoring policy implementation (em), which is measured based on the environmental policy monitoring files. The six different variables in the framework combined form the conditions for analysis: technology availability (ta) indicates the development of technology necessary to achieve the desired objectives; change required (cr) is measured by the number of heavy-pollution days and determines the extent of change; financial resources (fr) denotes the financial support provided for environmental protection; implementing officials (io) indicates the officials familiar with the statutes in question; public support (ps) reflects cases of polluting activities reported by the public; and socio-economic conditions (se) are measured by GDP *per capita*. Table 1 summarizes the operationalization of the data set and the data sources.

To operationalize the tractability of the problem, the first causal condition considered was technology availability. The numbers of compulsory cleaner production audits and evaluation firms were examined. A decade ago, the Chinese government passed a law named the Cleaner Production Audit to encourage companies to improve their technology. Specifically, firms that passed the compulsory cleaner production audit and evaluation consistently have higher technology availability than other firms. Measuring of the extent of behavioural change required is somewhat bit complex, and both the SO_2 and greenhouse gas emissions have been considered (Durant, 1984). The sample in the present study was selected based on the number of heavy-pollution days of cities at prefecture level and above. Having a larger number of heavy-pollution days appears very likely to threaten the successful implementation of environmental policy, as a larger number is associated with increased difficulty. For example, some provinces have more heavy-pollution days, such as Hebei, Henan and Shandong.

This article regards financial resources and implementing officials as statutory variables, and they are measured by the total investment in environmental pollution and the number of environmental monitoring staff members with the relevant certificates, respectively. It is obvious that during the policy implementation process, money is necessary to hire staff and conduct technical analysis. Given the unbalanced economic development in China, I use the percentage of total investment in environmental pollution treatment divided by regional GDP to measure financial resources (McFarlane, 1989). A high percentage indicates substantial financial resources. Because the number of environmental monitoring staff members varies across provinces, I measure implementing officials using the percentage of the number of environmental monitoring staff with a certificate divided by the total number of staff numbers. A high percentage is thus associated with the staff being highly familiar with the relevant legislation.

To operationalize non-statutory aspects, this study measures the percentage of the number of reported cases from WeChat divided by a region's total population at year-end and GDP *per capita* (Zhan et al., 2014). This information was obtained from China Environment Yearbook 2017 and China Statistical Yearbook 2016. However, because GDP indicator does not capture sufficient information about different provinces' economic conditions, I operationalize socio-economic conditions using GDP *per capita* (Xu, 2011). We expect that provinces with high GDP *per capita* belong to high socio-economic condition groups. The provinces located in western regions always have poor socio-economic conditions relative to other provinces.

How do combinations of technology availability, change required, financial resources, implementing officials, public support and socio-economic conditions influence environmental

TABLE 2 Anchors for calibration.

Causal conditions and outcome	Calibration		
	Fully in	Crossover point	Fully out
Implementation (em)	0.80	0.67	0.47
Technology availability (ta)	648.000	236.000	66.500
Change required (cr)	599.500	396.500	126.500
Financial resources (fr)	0.0361	0.024	0.011
Implementing officials (io)	0.923	0.730	0.392
Public support (ps)	1.156	0.753	0.464
Socio-economic (se)	105,970.000	79,811.500	48,992.500

monitoring policy implementation? Although it is difficult to identify all environmental policies, it is possible to analyse environmental monitoring policies in China. Environmental monitoring policy implementation was operationalized in terms of the percentage of policies designated for environmental monitoring divided by the number of environmental monitoring policy files on these policies.

3.2 Calibration strategy

The first step of fsQCA analysis is calibrating the outcome and the causal conditions to determine their fuzzy set membership scores. The calibration is based on a certain number of thresholds or anchors and translates the raw numerical data into set membership scores (Duşa, 2018). There are three principles for effective calibration: first, clearly define the outcome and causal conditions; second, designate sensible thresholds or anchors; and third, transparently report the chosen thresholds (Greckhamer et al., 2018). Table 2 shows the anchors of the sets according to the basic principles of calibration. The software employed in the analysis of the raw numerical data was the Set Method packages in R software, which yielded a fuzzy calibrated condition (Duşa, 2018). This article uses the "direct method" approach to calibration, which means that the new value is a continuous number between 0 and 1 (Ragin, 2009). The thresholds have different types, where "Fully in" denotes complete inclusion in this set, "Crossover" is the crossover point, and "Fully out" is the threshold for complete exclusion; the three numbers are the actual threshold values (Duşa, 2018). For example, the label "Implementation (em)" measures the environmental monitoring policy implementation in a given province. In other words, a province with percentage scores below the crossover point of 0.67 might still engage in implementation, but the province is more out than in. Based on the existing calibration standards, this study set the intersection calibration standards for technology availability, change required, financial resources, implementing officials, public support, and socio-economic conditions to the 0.5 per centile and the full membership calibration standard to the 0.95 per centile. Conditions to the 0.5th percentile for the intersection calibration criterion, the full membership calibration criterion to the 0.95th percentile, and the full non-membership calibration criterion to the 0.05th percentile. The specific calibration anchors for each variable are shown in Table 3.

4 Results

4.1 Analysis of necessity for the outcome

The optimal approach for this study was to use the fs-QCA software, which contains the "Truth Table Algorithm" to conduct fuzzy-set analysis. The first step was to test whether a single variable was necessary for the outcomes. The minimal consistency threshold for necessity was set at 0.9 (Ragin, 2009). Neither the presence nor the absence of any of the 4 conditions is a necessary condition for the presence of good policy implementation outcomes. Necessity testing was conducted for the antecedent conditions and their negations of different transformation modes to eliminate the risk of missing necessary conditions in the parsimonious solution. Table 4 shows the results of the necessity analysis using fsQCA3.0 software. Based on the requirement that the consistency level of necessary conditions should be greater than 0.9, none of the conditional variables in this study could constitute a necessary condition for policy implementation. However, our fs-QCA analyses suggest that the absence of public support and the absence socio-economic conditions are the necessary conditions for policy implementation; of course, these two conditions are supersets of the outcome, meaning that policy implementation cannot be achieved without them.

4.2 Analysis of environmental monitoring policy implementation

Next, we tested sufficiency with a truth table representing all logically possible combinations of different variables. The design of the truth table was based on the Quine-McCluskey algorithm. The environmental monitoring policy implementation outcome was considered sufficient if the raw consistency value was above 0.8 (Ragin, 2009). For example, a value of 0.8 suggests that 80% of the cases with specific configurations are effective. The test of sufficiency for the environmental monitoring policy implementation outcome represents 64 logically possible combinations of the six variables.

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TABLE 3 Set member scores after calibration.

Province	Implementation	Technology availability	Change required	Financial resource	Implementing officials	Public support	Socio-economic
Anhui	0.257	0.322	0.019	0.330	0.475	0.003	0.021
Beijing	0.981	0.039	0.019	0.655	0.971	0.763	0.987
Chongqing	0.070	0.035	0.013	0.029	0.916	0.009	0.116
Fujian	0.404	0.083	0.013	0.021	0.885	0.722	0.380
Gansu	0.963	0.034	0.013	0.163	0.263	0.030	0.007
Guangdong	0.092	0.016	0.013	0.013	0.021	0.991	0.365
Guangxi	0.274	0.111	0.013	0.056	0.376	0.022	0.018
Guizhou	0.914	0.027	0.013	0.044	0.698	0.003	0.012
Hainan	0.162	0.022	0.013	0.025	0.002	0.004	0.033
Hebei	0.995	0.381	0.990	0.074	0.181	0.040	0.029
Heilongjiang	0.082	0.016	0.022	0.058	0.593	0.025	0.023
Henan	0.918	0.292	0.999	0.034	0.301	0.056	0.028
Hubei	0.188	0.109	0.033	0.107	0.984	0.006	0.091
Hunan	0.999	0.550	0.016	0.020	0.849	0.005	0.039
Inner Mongolia	0.648	0.036	0.016	0.594	0.113	0.007	0.323
Jiangsu	0.150	0.995	0.080	0.043	0.544	0.045	0.872
Jiangxi	0.975	0.065	0.015	0.182	0.431	0.028	0.023
Jilin	0.977	0.029	0.019	0.017	0.818	0.034	0.077
Liaoning	0.360	0.161	0.034	0.028	0.391	0.024	0.059
Ningxia	0.887	0.024	0.013	0.877	0.991	0.373	0.042
Qinghai	0.897	0.016	0.013	0.408	0.999	0.002	0.030
Shaanxi	0.991	0.037	0.276	0.164	0.892	0.043	0.060
Shandong	0.882	0.578	0.783	0.060	0.380	0.020	0.258
Shanghai	0.016	0.023	0.014	0.024	0.644	0.125	0.984
Shanxi	0.984	0.083	0.136	0.981	0.341	0.074	0.014
Sichuan	0.387	0.016	0.067	0.034	0.995	0.005	0.022
Tianjin	0.036	0.028	0.029	0.009	0.202	0.592	0.981
Xinjiang	0.920	0.023	0.037	0.873	0.652	0.014	0.023
Yunnan	0.934	0.080	0.013	0.043	0.994	0.005	0.009
Zhejiang	0.083	0.652	0.014	0.098	0.382	0.316	0.640

Table 5 is the part of the truth table that contains only rows with sufficient empirical evidence. In other words, each row covers at least one case in this truth table.

In this analysis, positive cases are set to true while negative cases, indifferent cases and remainders are set to false to find the most complex solution. We used standard analysis after the truth table was constructed because this procedure can provide complex, intermediate and parsimonious solutions (Ragin, 2009).

To resolve the limited diversity and counterfactual problems, we assumed that the variables present as directional expectations for all conditions expect change required (cr) and socio-economic conditions. Some provinces faced difficulties due to the amount of change required, and as discussed above, the more behavioural change is required, the more difficult successful environmental monitoring policy implementation; however, some polices that require substantial behavioural change seem to be implemented quite smoothly (O'Toole, 1986). This is why I base my assumption on the directionality of the change required based on the presence or absence of other factors. For socio-economic conditions (se), because local government leaders are critical and influence

TABLE 4 Analysis of necessity for the outcome.

Conditions	Consistency	Coverage
Technology availability (ta)	0.195	0.695
Change required (cr)	0.210	0.978
Financial resources (fr)	0.343	0.984
Implementing officials (io)	0.685	0.691
Public support (ps)	0.130	0.517
Socio-economic (se)	0.174	0.464
Absence of Technology availability (~ta)	0.890	0.618
Absence of Change required (~cr)	0.830	0.551
Absence of Financial resources (~fr)	0.757	0.551
Absence of Implementing officials (~io)	0.436	0.598
Absence of Public support (~ps)	0.922	0.627
Absence of Socio-economic (~se)	0.925	0.687

Note: Necessity condition analysis. On behalf of the fuzzy variables in bold (ta, cr, fr, IO, ps, se) and the fuzzy variable (~ta, cr, fr, ~~IO, ~ps, ~se).

environmental monitoring policy implementation, I make no assumptions for this condition. Based on theory and common sense, I expect technology availability (ta), implementing officials (io), financial resources (fr), and public support (ps) to contribute to the outcome when present. In other words, the absence of a requisite technology hinders successful environmental monitoring policy implementation. Having implementing officials who understand the policy, environmental expenditures, and public support for environmental policy positively influence implementation. The intermediate solution was obtained based on the above assumptions.

The intermediate solution has a consistency value of 0.958 and explains 55.587% of the cases that are coded as environmental monitoring policy implementation. This represents a comprehensive explanation of environmental monitoring policy implementation by using the six different variable combinations. Based on this, Table 6 shows formula for the intermediate solution. The discussion section will provide further details on the explanations of the intermediate solution.

4.3 Robustness tests

This paper examines the robustness of pathways that produce high environmental monitoring policy implementation effects. QCA is an ensemble theory approach that is regarded as robust when slight changes to the operations, with subset relationships between the resulting outcomes, do not change the substantive interpretation of the study's findings. QCA is a set theory approach that is based on the idea that the results of a policy implementation are not necessarily the same as the results of a policy implementation. Based on this, this study examines the four aspects of (adjusting raw consistency) adjustmentraw consistency value; changed condition crossover point; altering the operationalisations and comparative analysis of the results of the policy implementation, respectively. Robustness of the results. In the first robustness test, the same seven indicators for environmental monitoring policy implementation are included, but the raw consistency value is altered. The raw consistency value of environmental monitoring policy implementation in the original analysis was set at 0.80. In the alternative calculation, while we altered the raw consistency value to 0.85, the analysis of the conditions yielded the same configurations as the original analysis. The truth table also covered the same cases. Table 7 provides details on the configurations and results.

In the second robustness test, we changed the socio-economic conditions (se) crossover point from 79,811.5 to 81,529.6. The World Bank categorizes the world's economies into four income groups based on GNI *per capita*. The thresholds for low, lower-middle, upper-middle, and high by income are $1,025, $4,035 and $12,475, and the exchange rate between the USD and the CNY was $1 to ¥6.6423 in 2016. We set a new crossover point based on the percentage of GDP *per capita* of $8,117.27 and GNI *per capita* of $8,250 in 2016. Table 8 shows that altering the thresholds did not change the conclusions.

Generally, the robustness tests also change the operationalization of public support to the percentage of the number of reported cases from letters and visits divided by the region's total population at year-end (LV). Table 9 shows that altering the operationalizations does not significantly change the results of the analysis.

4.4 Analysis of no environmental monitoring policy implementation

Table 10 shows the intermediate solution for the outcome of no environmental monitoring policy implementation. The configurations observed in the case of no environmental monitoring policy implementation are different combinations than those observed in the case of environmental monitoring policy implementation, which also demonstrates the robustness of the environmental monitoring policy implementation configurations.

5 Discussion

The intermediate solution analysis for the environmental monitoring policy implementation outcome suggests 4 paths. This leads to four configurations of the hexagon, which reflect the various combinations of the variables influencing environmental monitoring policy implementation. The configurations are named as follows: 1) priority governance, 2) money talks, 3) coordinated implementation, and (4) comprehensive strategy.

Table 11 shows the four configurations of environmental monitoring policy implementation. The first row of this table provides a graphical illustration based on the Boolean expressions of each variable composing the hexagon. The chart that reports 1 and 0 values indicates the presence and absent absence of the variables according to the intermediate solution. While in some combinations, are of the variables all sufficient for causing high implementation, the prime combinations can be simplified; an "r" that lies between the values 1 and 0 means that the finding is logically redundant. When we observe the intermediate position, the variables might be either present in or absent from

TABLE 5 Truth table for the environmental monitoring policy implementation outcome.

Technology availability	Change required	Implementing officials	Financial resources	Socio-economic	Public support	No.	Implementation	Raw consist	PRI consist	SYM consist	Cases
0	1	0	0	0	0	2	1	1.000	1.000	1.000	Hebei, Henan
1	1	0	0	0	0	1	1	1.000	1.000	1.000	Shandong
0	0	1	1	1	1	1	1	0.979	0.967	0.967	Beijing
0	0	1	1	0	0	2	1	0.976	0.961	0.961	Ningxia, Xinjiang
0	0	0	1	0	0	2	1	0.970	0.947	0.947	Shanxi, Inner Mongolia
1	0	1	0	0	0	1	1	0.867	0.685	0.685	Hunan
0	0	1	0	0	0	9	0	0.703	0.596	0.628	Jilin, Heilongjiang, Hubei, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Qinghai
0	0	1	0	0	1	1	0	0.690	0.137	0.144	Fujian
0	0	0	0	0	0	6	0	0.656	0.477	0.492	Liaoning, Anhui, Jiangxi, Guangxi, Hainan, Gansu
1	0	1	0	1	0	1	0	0.624	0.217	0.217	Jiangsu
0	0	1	0	1	0	1	0	0.598	0.296	0.296	Shanghai
1	0	0	0	1	0	1	0	0.553	0.179	0.179	Zhejiang
0	0	0	0	0	1	1	0	0.462	0.073	0.073	Guangdong
0	0	0	0	1	1	1	0	0.361	0.052	0.052	Tianjin

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TABLE 6 Intermediate solution formula for the environmental monitoring policy implementation outcome.

Sufficient paths, connected by logical OR[a]	Consistency	Cov.r[b]	Cov.u[b]
CR*se	0.985	0.206	0.110
FR*se	0.984	0.306	0.198
TA*IO*se	0.895	0.168	0.051
cr*IO*FR*PS	0.985	0.090	0.037

Notes: Capital letters indicate presence; small letters indicate absence; and *denotes logical AND., Cov. r[b] means raw coverage; Cov.u[b] means unique coverage.

TABLE 7 Intermediate solution formula for the environmental monitoring policy implementation outcome (0.85 consistency).

Sufficient paths, connected by logical OR[a]	Consistency	Cov.r[b]	Cov.u[b]
CR*se	0.985	0.206	0.110
FR*se	0.984	0.306	0.198
TA*IO*se	0.895	0.168	0.051
cr*IO*FR*PS	0.985	0.090	0.037

Notes: Capital letters indicate presence; small letters indicate absence; and *denotes logical AND., Cov.r[b] means raw coverage; Cov.u[b] means unique coverage.
Solution coverage: 0.546; Solution consistency: 0.958.

TABLE 8 Intermediate solution formula for the environmental monitoring policy implementation outcome (new thresholds).

Sufficient paths, connected by logical OR[a]	Consistency	Cov.r[b]	Cov.u[b]
CR*se	0.986	0.207	0.111
FR*se	0.984	0.305	0.198
TA*IO*se	0.889	0.167	0.051
cr*IO*FR*PS	0.985	0.090	0.037

Notes: Capital letters indicate presence; small letters indicate absence; and *denotes logical AND. Cov.r[b] means raw coverage; Cov.u[b] means unique coverage.
Solution coverage: 0.547; Solution consistency: 0.957.

TABLE 9 Intermediate solution formula for the environmental monitoring policy implementation outcome (new operationalization).

Sufficient paths, connected by logical OR[a]	Consistency	Cov.r[b]	Cov.u[b]
CR*se	0.985	0.206	0.110
FR*se	0.984	0.306	0.217
TA*IO*se	0.895	0.168	0.051
cr*IO*FR*LV	0.983	0.077	0.037

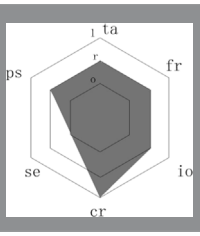
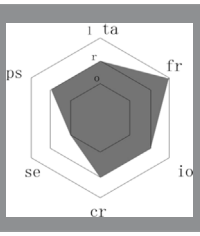
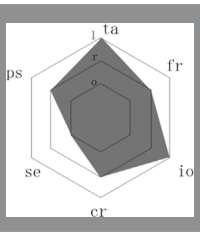
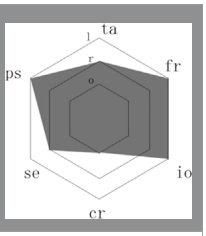
Notes: Capital letters indicate presence; small letters indicate absence; and *denotes logical AND., Cov.r[b] means raw coverage; Cov.u[b] means unique coverage.
Solution coverage: 0.546; Solution consistency: 0.958.

TABLE 10 Intermediate solution formula for the no environmental monitoring policy implementation outcome.

Sufficient paths, connected by logical OR[a]	Consistency	Cov.r[b]	Cov.u[b]
cr*fr*ps*SE	0.894	0.326	0.144
ta*cr*fr*PS*se	0.954	0.157	0.055
ta*cr*fr*io*SE	0.917	0.226	0.031

Notes: Capital letters indicate presence; small letters indicate absence; and *denotes logical AND.
Cov.r[b] means raw coverage; Cov.u[b] means unique coverage.
Solution coverage: 0.440; Solution consistency: 0.913.

TABLE 11 The complexity of environmental monitoring policy implementation.

Policy implementation (connected by logical OR)				
Configuration	Priority governance	Money talks	Coordinated implementation	Comprehensive strategy
Sufficient path	CR*se	FR*se	TA*IO*se	cr*FR*IO*PS
Most typical	Hebei, Henan, Shandong	Xinjiang, Shanxi, Ningxia, Inner Mongolia	Hunan	Beijing
Uncovered	Shanxi, Jilin, Jiangxi, Gansu, Yunnan, Guizhou, Qinghai			

Notes: 0 indicates absence; 1 indicates presence; and r indicates logically redundant TA (technology availability), CR (change required) FR (financial resources), IO (implementing officials), PS (public support), SE (socio-economic conditions).

environmental monitoring policy implementation. However, they are not necessary to ensure the outcome because of the logical minimization. Since some cases are not explained by the hexagons, in the last row, the table reports the cases that are not covered by the solution formula but have high environmental monitoring policy implementation.

The first configuration of the hexagon is referred to as "Priority Governance". The results of the first set of data show that the value of CR is 1, which represents the existence of the core condition; the value of se is 0, which represents the existence of the edge condition, and the value of ps,ta,fr, io is located between 0 and 1, which is a non-essential condition, i.e., it is logically redundant. Thus, CR*se is the Sufficient path, in addition, the results also show that Hebei, Henan, Shandong are the typical provinces that conform to this path in the context of China's environmental policy implementation. Since provinces in this group prioritize solving pollution problems and are characterized by a combination of substantial change required and poor socio-economic conditions related to environmental monitoring policy implementation. Such efforts are supported by substantial numbers of heavy-pollution days for cities at the prefectural level and above, which represent the foundational drivers of environmental monitoring policy implementation in China. The typical cases of environmental monitoring policy implementation are Hebei, Henan, and Shandong. These cases are difficult to interpret under the framework because the mixed tractability results nevertheless yield substantial environmental monitoring policy implementation; however, the basic hypothesis of Sabatier and Mazmanian (1980) is "the greater amount of behavioral change required, the more problematic successful implementation will be". Typical cases showing this configuration of the hexagon are the Hebei, Henan, and Shandong–all of which are provinces with cities at the prefecture level and above with a high number of heavy-pollution days–and they illustrate the amount of behavioural change required to stimulate environmental monitoring policy implementation under Chinese conditions. This result can be explained by the Chinese governing system, specifically, the dual leadership of the local EPBs and the "One-vote negation system" for local government. For local EPBs, environmental monitoring policy implementation is often subject to contradictory demands, vertically from the central government and horizontally from local governments. Although the amount of behavioural change required is substantial and other variable resources are limited, combinations of these variables may still encourage the environmental monitoring policy implementation. For local government, a possible motivation is that the greater pressure from the central government results in implementation agencies attempting to collaborate to secure other resources associated with perceived environmental monitoring policy implementation. By contrast, the limited pressure experienced in provinces with fewer heavy-pollution days requires more combinations of other variables, as discussed above.

The second configuration - "Money makes the Devil work". From the results of the second set of data, it can be seen that the value of FR is 1, which represents the existence of core conditions; the value of se is 0, which represents the existence of marginal conditions, and the values of ps,ta,cr, io are located between 0 and 1, which are non-essential conditions. Thus, FR*se is the Sufficient path. In addition, the results of the study show that in the context of China's environmental policy implementation, Xinjiang, Shanxi, Ningxia, Inner Mongolia are the typical provinces that conform to this path. Combined with the actual situation of the above provinces in China, the provinces mobilize financial resources, namely, they are characterized by a combination of substantial financial resources and lower socio-economic conditions. In other words, environmental monitoring policy implementation can be influenced by investment in environmental pollution treatment. Compared with the other configurations of the environmental monitoring policy implementation, the variables in this category intensively use environmental investments, as the name of the configuration suggests. The configuration includes almost all cases located in north-western China, and the only uniquely covered province—Shanxi—is also located in the northern part of China. Most cases of environmental monitoring policy implementation need not include many variables at once, as this configuration indicates. Regarding socio-economic conditions, it seems that poor regions spend substantial amounts of money on environmental monitoring policy implementation. This is similar to the viewpoints of some previous scholars in the field of environmental monitoring policy, in which Sadik-Zada and

Ferrari., 2020 scholars pointed out that the structural composition of the economy and the level of economic development (or the government's financial resources) are the main, but not the only, factors affecting the effectiveness of the implementation of a country's environmental policy (2020). Generally speaking, the lower the socio-economic conditions of a region, the greater the level of pollution, on the contrary, will be relatively large, which also increases the region's investment in the environment.

The third configuration of environmental policy implementation is called "coordinated implementation". From the results of the third set of data in Table 11, it can be seen that the value of TA and IO is 1, which is the core condition of this path; the value of se is 0, which is the edge condition of this path, and the value of ps,fr, cr is located between 0 and 1, which is the non-essential condition of this path. Thus, TA*IO*se is the Sufficient path, in addition, we can find that Hunan is a typical province that meets this path from the data. This configuration is named "coordinated implementation" because of the high technical availability, more familiarisation of the implementing officials with the policy, and lower socio-economic conditions. This configuration is more complex because it includes both the operability of the problem and the ability to organise the implementation of the regulation. Due to the combination of high technology availability, implementation officials who are more familiar with the policy, and lower socio-economic conditions. This configuration is more complex because it includes the aspects of both the tractability of the problem and the ability of statute to structure implementation. Regarding the technology availability and implementation officials in particular, it seems that promoting compulsory cleaner production audit and evaluation firms and training environmental monitoring staff are needed to ensure environmental monitoring policy implementation. That the Communist Party of China consistently provides overall leadership and coordinates the efforts of all involved can explain why coordinated implementation can lead to environmental policy effectiveness. This is the case in Hunan, the province with the highest environmental monitoring policy implementation. Since the officials can monitor the progress of the audit and evaluation and are familiar with the monitoring policies, environmental monitoring policy implementation can be influenced by the intervention of street-level bureaucrats. In addition, similar to previous studies, the environmental Kuznets curve developed by Sadik-Zada and Gatto, 2023 scholars shows that high-quality environmental monitoring policy implementation and governance outcomes can be achieved in selected developing countries with average socio-economic conditions. "Growth before governance" is no longer the common paradigm for environmental governance (2023). Therefore, it is a somewhat useful configuration of the hexagon for improving environmental monitoring policy implementation in China.

From the results of the fourth set of values in Table 11, it can be observed that FR, IO and PS have a value of 1 and therefore are the core conditions of this pathway, while cr has a value of 0 and therefore represents the marginal conditions of this pathway. Ta and se have values between 0 and 1 and are the non-necessary conditions of this drywell. From this, cr*FR*IO*PS is the Sufficient path, in addition, we can find from the data that Beijing is the typical province that meets this path. The name is based on the assumption that environmental monitoring policy implementation relies on a combination of less change being required, implementing officials who are relatively familiar with the legislation, having substantial financial resources and possessing sustained public support. A typical case where the hexagon is in this configuration is Beijing, the capital of China. Furthermore, the central government, together with ministries and commissions, is located in Beijing. The approval of the central government supports and the substantial resources provided by the various ministries which results in environmental monitoring policy implementation even though little change is required for Beijing. However, this is a specific and irrational combination, and it is difficult for other provinces to secure the same resources and support. Therefore, the hexagon representing this configuration is not stable, but it nevertheless leads to environmental monitoring policy implementation.

6 Conclusion

This paper applies the fs-QCA qualitative research methodology to categorise the antecedent variables affecting the implementation of environmental monitoring policies in China, and explores the impact of the combined configurational effects of these variables on the effectiveness of policy implementation. Specifically, based on the policy implementation process framework (Sabatier and Mazmanian, 1980), this study analytically examines the effects of different combinations of technology availability, change required, financial resources, implementing officials, public support, and socio-economic conditions on the implementation of environmental monitoring policies, following an assessment of 30 provinces in China. Among them, the four hexagonal configurations proposed in this paper provide new explanations for the reasons for differences in environmental monitoring policy implementation in different provinces.

Our study provides considerable insights into the implementation of environmental monitoring policies and confirms previous findings in the literature on the variables involved in the policy implementation process. It is not difficult to find from previous studies that most scholars have ignored the impact of the combined configuration effect of antecedent variables of policy implementation on the effectiveness of policy implementation based only on case studies. Although our results differ slightly from those in the Sabatier and Mazmanian (1980) framework, it could nevertheless be argued that these differences are due to the Chinese governance system and the country's socio-economic conditions. Apart from this slight disagreement, the results in this work confirm the variables that should be considered in environmental monitoring policy implementation by using more sophisticated methods. Initially, we believed that Western theories could be applied to China. However, a more careful analysis revealed that the application of Western policy research requires localization and contextualization. The discussion of the findings revealed that no specific variables in the hexagon alone can influence environmental monitoring policy implementation. Several provinces attempt to consider the tractability of the problem and the extent of behavioural change required, such as Hebei, Henan and Shandong. Those with poor economic performance, including Xinjiang, Shanxi, Ningxia and Inner Mongolia, require more financial resources related to environmental monitoring policy implementation, possibly because of their economic structure and geographic location. However, the highest level of environmental monitoring policy implementation demands technology availability and implementation officials to

ensure that it is effective, for example, in Hunan. By absorbing nationwide resources, the capital of China, Beijing, demonstrates that implementing officials, financial resources, social-economics and public support influence environmental monitoring policy implementation. Further study of the different variable combinations would help provinces improve environmental monitoring policy implementation.

A number of limitations may have influenced the results of this study, which seems reasonable. First, this paper uses provincial data with a duration of 1 year, while the policy implementation process is dynamic. Therefore, future research could use dynamic panel data with a time horizon of many years to better explore the differential impact of group effects of multiple factors on the effectiveness of policy implementation at different points in time. Second, another possible research limitation is that the antecedent variables selected in this paper do not cover all the variables involved in the Sabatier framework. This is so because the fs-QCA approach requires a limitation on the number of antecedent variables. Therefore, future research should expand the sample size to include more influential factors that may affect the effectiveness of environmental monitoring policy implementation, thus making the study more systematic and standardised. Finally, the collection and design development of secondary data is a challenge for our study. In future studies, the survey and interview work with the relevant population demographics and environmental monitoring policy implementers should be strengthened to enhance the reliability of the findings.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

TJ: Conceptualization, Writing–original draft. HG: Conceptualization, Writing–review and editing. GC: Data curation, Writing–review and editing. XD: Formal Analysis, Writing–review and editing. WX: Formal Analysis, Writing–review and editing. ZW: Methodology, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Impact on green finance and environmental regulation on carbon emissions: evidence from China

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Introduction: Achieving peak carbon dioxide emissions and carbon neutrality is an extensive and profound systematic economic and social change. Through market-oriented financial means, green finance has moved forward the effective governance port, curbed polluting investment and promoted technological progress such as green low-carbon, energy conservation and environmental protection, which has become a powerful starting point to support the practice of low-carbon development.

Methods: Based on the panel data of 30 provinces in China (except Tibet, Hongkong, Macau and Taiwan Province) from 2004 to 2021, this paper calculates the development level of green finance in China provinces by using entropy weight method, and on this basis, uses mathematical statistical model to verify the impact of green finance and its sub-dimensions on carbon emissions and the regulatory effect of heterogeneous environmental regulation tools.

Results: The results show that the development of green finance has a significant inhibitory effect on carbon emissions during the investigation period, and there is a time lag effect. After a series of robustness tests and considering endogenous problems, this conclusion still holds. From the results of heterogeneity analysis, the carbon emission reduction effect of green credit is the most obvious, and the impact of green finance on carbon emission is slightly different in different regions. Besides, Command-controlled environmental regulation tools and public participation environmental regulation tools play a positive regulatory role in the transmission path of green finance's impact on carbon emissions, but market-driven environmental regulation tools cannot effectively enhance the carbon emission reduction effect of green finance development.

Discussion: The research results of this paper provide a basis for the government to formulate flexible, accurate, reasonable and appropriate green financial policies, help to strengthen the exchange and cooperation between regions in reducing carbon and fixing carbon, and actively and steadily promote China's goal of "peak carbon dioxide emissions, carbon neutrality".

KEYWORDS

green finance, heterogeneous environmental regulation, carbon dioxide emissions, regulatory effect, high-quality development

1 Introduction

Since the reform and opening up, China's economic construction has made great achievements, created the China miracle in the history of human economic development, and made China contribution to the world's economic development. However, the rapid economic growth is at the cost of resource consumption, environmental pollution and ecological degradation. The long-term development mode of extensive economic has made environmental problems such as resource and environmental constraints and ecological degradation more and more prominent, and various environmental pollution and ecological destruction have occurred frequently. China has become the largest energy consumption and carbon emission country in the world (Lin, 2022). The report "Global Environmental Performance Index 2020″shows that China's environmental performance ranking is in a relatively low position among more than 180 countries participating in the ranking, and the environmental quality scores of methane intensity, carbon dioxide intensity and nitrogen oxide intensity are low (Latif, 2022). With the consensus of green and low-carbon development in the world, how to effectively deal with the increasingly severe carbon emission pressure and achieve the goal of "double carbon" as scheduled has become an urgent practical problem to be studied. The development of green economy needs a lot of capital investment, and financial resources can only meet 10%–15% of it (Zhang et al., 2021). Faced with such a huge demand for carbon reduction funds and the pressure of economic transformation, green finance has become an inevitable choice to conform to this trend.

Green finance, also known as "environmental finance" or "low-carbon finance", is a variety of institutional arrangements and financial services to promote the development of low-carbon economy, and plays an active role in guiding the rational allocation of resources, promoting the ecological development of traditional industries and the development of new green ecological industries. Taking green credit as an example, the differentiated reward and punishment of credit costs for green enterprises and polluting enterprises has released an incentive or warning signal to related enterprises, which has enabled similar enterprises to spontaneously adjust their development models and transform to green. At the same time, the "green signal" transmitted by green finance through the design of market mechanism plays a role in mobilizing social capital, guiding social capital to lay out green industries and providing necessary capital demand for ecological environment governance. Therefore, with the increasingly severe situation of carbon emission in China, green finance has become an important way to promote the construction of ecological civilization and win the battle of pollution prevention and control, and it is the key support and effective grasper to achieve the goal of "double carbon".

So, does the development of green finance really help to reduce carbon emissions? The research on this issue is undoubtedly of great significance in realizing the goal of "double carbon", constructing the institutional guarantee for low-carbon development and promoting the green transformation of development mode.

The rest of the article is arranged as follows: the second chapter provides a literature review on the measurement and evaluation of green finance, the influencing factors of carbon emissions and the relationship between green finance, environmental regulation and carbon emissions; the third chapter puts forward the research hypothesis of this paper, combs the influence path of green finance on carbon emissions and what role environmental regulation policy plays in this process; the fourth chapter describes the data and methods used in this paper; the fifth chapter uses a series of mathematical statistical models to verify the carbon emission reduction effect of green finance and the regulatory effect of environmental regulation; the sixth chapter summarizes the full text, provides corresponding policy suggestions, and expounds the research limitations and future prospects. See Figure 1 for an overview of the article.

2 Literature review

Looking at the relevant literature at home and abroad, the research related to the theme of this paper can be roughly divided into the following aspects.

2.1 Measurement and evaluation of green finance

The existing literature has conducted extensive and in-depth research on the measurement of the development level of green finance from both macro and internal mechanisms, and most scholars adopt the method of multiple indexes weighting to measure it. For example, Clark et al. (2018), Yin et al. (2022), and Meo et al. (2022) selected the development indicators of green finance from four areas: green credit, green securities, green insurance and carbon finance, and found that green finance could not be effectively linked with industrial structure adjustment, ecological environment protection and economic development, and the degree of green finance was not high, which restricted the coordinated development of green finance and economic growth, resulting in the insignificant supporting role of green finance for economic growth. Lv et al. (2021) constructed the evaluation index system of green finance from five dimensions: green credit, green securities, green insurance, green investment and carbon finance. By using Dagum's Gini coefficient decomposition method, nuclear density estimation, Markov chain and spatial Markov chain, it was found that the overall development index of green finance in China showed an upward trend, but the overall level was not high, and the regional gap was gradually narrowing.

2.2 Research on the influencing factors of carbon emissions

Most of the existing literatures use LMDI exponential decomposition method and STIRPAT model to study the influencing factors of carbon emissions. For example, the level of economic growth, energy intensity, energy structure, industrial structure, foreign direct investment and technological innovation are the main factors that affect carbon emissions (Muhammad et al., 2013; Qin et al., 2022; Liu et al., 2023). Yu et al. (2019) and

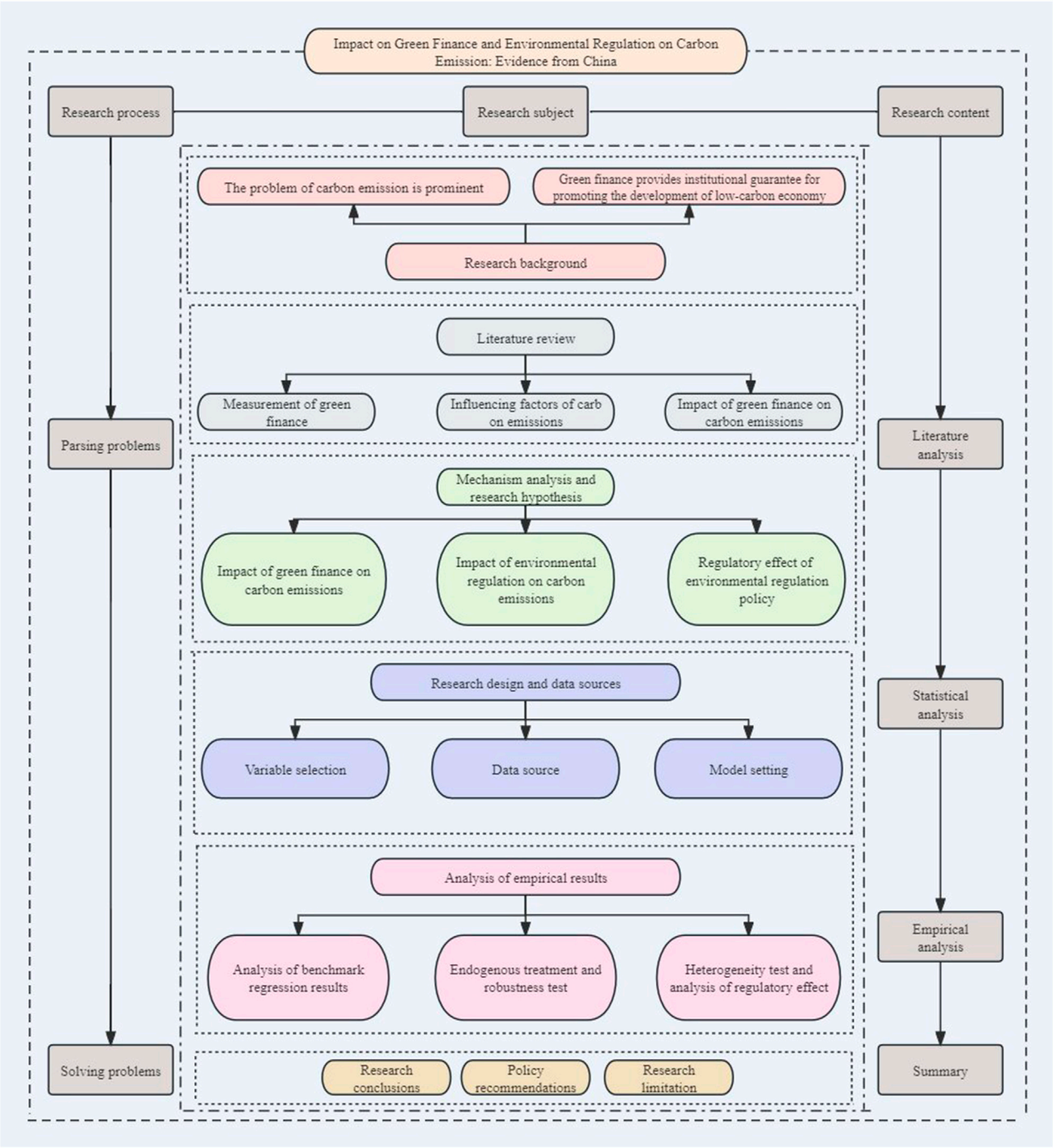


FIGURE 1
General picture of research.

Zhang et al. (2022) pointed out that using a stricter but properly designed environmental regulation tool will promote regulated enterprises to dynamically adjust their internal resource allocation under the background of changing constraints, improve the efficiency of green technology innovation, and partially or even completely offset the cost of complying with environmental regulation, thus improving the market competitiveness of enterprises and solving the regional environmental pollution problem.

2.3 Research on the relationship between green finance, environmental regulation and carbon emissions

Academic circles have done a lot of theoretical discussion and empirical analysis, but there are still great differences between the existing conclusions. There is no agreement on what role green financial development plays in carbon emissions. The implementation of green financial policy guides capital to

support green projects such as environmental protection industry and clean energy by reducing financing costs, relaxing quota restrictions and increasing financial leverage, thus promoting environmental protection transformation and technological upgrading of enterprises and reducing carbon emissions. However, some scholars hold the opposite view, such as Huang and Tian (2023), Kant et al. (2021) and Hou et al. (2022), indicating that the development of green finance may increase carbon dioxide emissions by expanding the production scale of enterprises and promoting consumption. In addition, the existing research has not reached an agreement on whether the environmental regulatory tools have the effect of carbon emission reduction, and the "strong Porter hypothesis" and "weak Porter hypothesis" coexist. Most scholars believe that environmental regulation obeys the effect of "innovation compensation", that is, the reverse effect of the policy itself promotes the transformation and upgrading of industrial structure, makes production factors flow to less polluting industries and eliminates backward production capacity. At the same time, some scholars believe that there is a "cost retrogression effect" in environmental regulation tools. Due to additional energy conservation and emission reduction and increased pollution control costs, enterprises and other production entities urgently need to adjust their production scale, which will reduce their productivity and market competitiveness to a certain extent.

To sum up, the existing literature has done a lot of useful research on measuring the development level of green finance in China, identifying the influencing factors of high carbon emissions and exploring the relationship between green finance, environmental regulation and carbon emissions, which provides ideas for reference and method enlightenment for this paper. However, the existing literature lacks attention to the nonlinear relationship between green finance and carbon emissions. At the same time, there are few documents from the perspective of heterogeneous environmental regulation policies to explore its regulatory effect in the process of carbon emission reduction of green finance.

The contribution of this paper is as follows. (1). According to the connotation and purpose of green finance, this paper constructs an evaluation index system of green finance development index from four dimensions: green credit, green securities, green insurance and green investment, and quantitatively evaluates the development level of green finance in China in multiple dimensions, thus more comprehensively reflecting the influence of green finance and its sub-dimensions on carbon emissions; (2). When combing the channel mechanism of green finance's impact on carbon emissions, the paper innovatively takes heterogeneous environmental regulation tools as regulatory variables and brings them into the analysis framework, so as to identify the effective channels for green finance to play the role of carbon emission reduction in China at this stage, further enriching the research content of green finance and providing useful reference for further optimizing the combination of environmental regulation tools; (3). Most of the existing studies focus on the static, dynamic and spatial spillover effects of green finance development on carbon emissions, and there is little research on whether there is a time lag effect between them. In this paper, the lagging period of green finance index is included in the model analysis, and the long-term relationship between green finance development and carbon emissions is discussed. (4). The paper clearly compares the differences of carbon emission reduction effects of green finance in different regions of China, expands the depth of research in this field, and provides an empirical basis for maintaining the consistency and stability of green financial policies, which is conducive to finding the starting point of green finance and accelerating the realization of "peak carbon dioxide emissions and carbon neutrality".

3 Mechanism analysis and research hypothesis

Based on the existing literature research and sustainable development theory, combined with the nature of green finance, this paper studies the influence mechanism of green finance on carbon emissions and the effect of environmental regulation policies. The specific theoretical logic framework is shown in Figure 2.

3.1 The impact of green finance on carbon emissions

3.1.1 Guidance drive effect

Green finance, as a new finance aimed at coping with climate change, improving ecological environment and efficiently utilizing resources, covers energy conservation, environmental protection, clean energy, green transportation, green agriculture, etc. By developing green credit, green bonds, setting up green development funds and other forms, it can leverage social idle capital to inject into the green environmental protection field, thus having a substantial impact on the "carbon reduction" activities (Chang et al., 2024; Yan et al., 2023a). Specifically, the environmental governance of enterprises usually has the characteristics of long period, high cost, high risk and high uncertainty, which leads to the traditional financial involvement, which hinders the promotion of carbon emission reduction to some extent (Zhao et al., 2023). Green finance can help economic growth by exerting "savings mobilization", and provide long-term and low-cost green financial capital for enterprises by using financial policies such as credit tilt and interest rate floating, and provide sufficient financial guarantee for carbon emission reduction, thus reasonably matching the risks and benefits of carbon reduction for enterprises (He et al., 2022; Chi et al., 2023). At the same time, as a top-down policy tool, green finance is not only reflected in the fact that financial institutions represented by banks are constantly raising the loan threshold of "three high" enterprises, restricting their interest-bearing debt financing and new investment, but also in the fact that it has an impact on the investment logic of market investment by setting up a weather vane of primary capital market, thus guiding social funds to flow from "three high" enterprises to green enterprises, further compressing the living space of enterprises with high energy consumption, high pollution and high emissions, and effectively promoting (Zhang et al., 2022; Wang et al., 2023). In addition, green

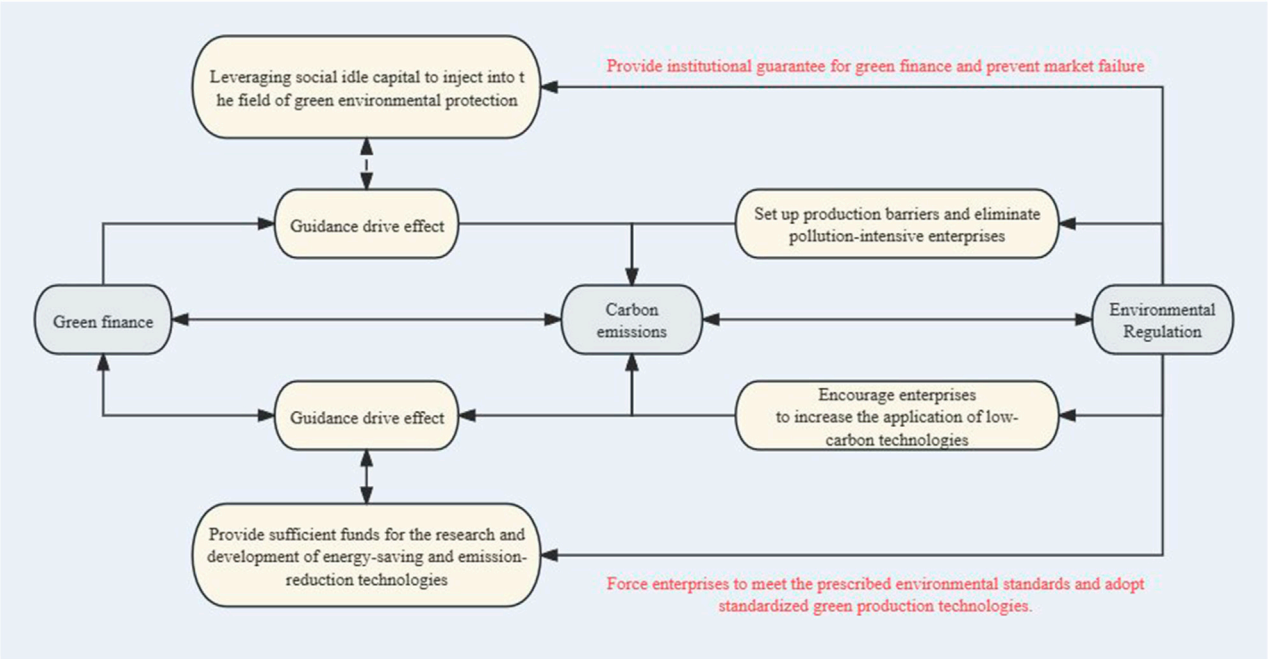


FIGURE 2
Mechanism analysis diagram.

finance integrates the development concept of low-carbon and environmental protection into the financial field, guides financial institutions to directly participate in environmental governance, and provides diversified, multi-level and flexible fund allocation, especially focusing on supporting the green transformation of infrastructure, projects in the field of clean energy and the development of energy-saving and environmental protection industries, so as to reduce carbon emissions and accelerate the development of green economy. However, it is worth noting that the policy formulation, product innovation and market cultivation of green finance need to be explored and practiced repeatedly to gradually show the effect, so as to effectively guide more funds to withdraw from the "two high and one surplus" field and flow to the "two low" field, and finally curb the carbon emissions generated by production activities and consumption behavior.

3.1.2 Technological innovation effect

As an important tool to coordinate the opposition between economic growth and environmental protection, green technological innovation plays an irreplaceable role in the green transformation of national economy (Xu et al., 2020; Lee et al., 2022). The first premise of technological progress is the effective investment of capital. Green finance, as a new financial model that gives consideration to both ecological environment protection and traditional financial activities, complements the shortcomings of the capital chain of clean production departments by exerting the financial functions of capital allocation, risk diversification and external incentives and constraints, and provides sufficient financial guarantee for the research and development of energy-saving and emission-reduction technologies, thereby improving carbon emission efficiency and reducing unnecessary carbon emissions (Han et al., 2022). Specifically, with the gradual improvement and maturity of the green financial system, green finance can develop diversified underlying assets for different environmental rights and interests, such as carbon trading, emission trading and water rights trading, thus broadening financing channels and breaking the capital bottleneck of technology research and development of different types of enterprises (Lv et al., 2023; Xu et al., 2023). At the same time, the continuous enrichment of financial products such as green securities and green bonds can not only meet different investment needs, but also reduce the threat to the company's technological innovation caused by "black swan" time and market fluctuation, and disperse the risk of technological research and development of enterprises, thus reducing the pressure of green management of enterprises. In addition, with the continuous improvement of corporate environmental information disclosure mechanism, ESG evaluation index will become a new investment criterion in the financial market, and different audit mechanisms and standards will be established for different green industries, which will cause banks and securities institutions to urge listed companies to disclose detailed and complete environmental information, especially carbon emissions and carbon footprint information of polluting enterprises, and to evaluate the green qualification of loan enterprises (Huang et al., 2023a; Xiong et al., 2023; Zeng et al., 2023). This will force polluting enterprises to increase technology research and development in order to obtain credit funds, promote the green transformation of enterprise production methods, and reduce the carbon dioxide emissions generated by daily production activities (Guo et al., 2022).

Based on the above analysis, the article puts forward the following assumptions:

Hypothesis 1: Developing green finance can inhibit carbon emissions. However, due to factors such as policy lag, there is a time lag in the carbon emission reduction of green finance.

3.2 Influence of environmental regulation on carbon emissions

With a series of problems, such as resource overdraft, ecological degradation and serious environmental pollution, brought about by extensive economic growth model, the ecological pressure in China has faced the environmental bearing limit. In order to achieve sustainable economic development and alleviate the negative effects of environmental pollution, the government has formulated relevant laws and regulations to implement the main responsibility of corporate environmental governance. Therefore, environmental regulation has become an important tool to promote the goal of "double carbon" and an important means to balance the relationship between economic development and ecological environmental protection (Wen et al., 2022; Liang and Song, 2022). Using a stricter but properly designed environmental regulation tool can effectively promote the regulated enterprises to dynamically adjust the internal resource allocation of enterprises under the background of changing constraints, improve the efficiency of green technology innovation, and partially or completely offset the cost of complying with environmental regulation, so as to improve the market competitiveness of enterprises and solve the regional environmental pollution problem (Zhong et al., 2015; Luo et al., 2023). Specifically, on the one hand, environmental regulation will set up barriers in increasing the capital required by pollution-intensive enterprises, improving the difficulty of commercial operation and stricter regulatory standards, so that market enterprises can realize the survival of the fittest, promote the upgrading of industrial structure and reduce carbon emissions (Pei et al., 2019). On the other hand, environmental regulation is conducive to low-emission enterprises to obtain support from policies and funds, and to achieve the sustainability of production and operation by improving the level of production technology and expanding their own production scale while increasing the investment and application of low-carbon technology innovation (Zhou et al., 2023).

Since the reform and opening-up, China is gradually building a "trinity" environmental regulation system with administrative orders, market incentives and public participation. The administrative imperative environmental regulation tool mainly relies on the rigid constraints of relevant administrative regulations, and compellingly requires enterprises and other market entities to control production and pollution discharge, thus promoting environmental improvement (Li et al., 2022). Market-driven environmental regulation is designed by the administrative subject according to the "polluter pays" principle, aiming at guiding enterprises to flexibly adjust the factor structure according to their own production and operation conditions by relying on the market regulation mechanism and collecting market means such as sewage charges, so as to reduce pollutant emissions (Qu et al., 2022). For public participation in environmental regulation tools, it comes from the pressure of individuals and social organizations on market operators such as enterprises. In the environmental governance system of "government-enterprise-public", media communication, public opinion pressure and public action will have a strong sense of oppression on environmental damage. According to the stakeholder theory, public participation in monitoring the pollution discharge behavior of enterprises will force enterprises to optimize their production behavior in advance and increase capital investment to introduce or develop green technologies, so as to realize the transformation from "end pollution control" to "source control" and promote the development of carbon emission reduction (Huang et al., 2023b).

Based on the above analysis, the article puts forward the following assumptions:

Hypothesis 2: Environmental regulatory policies can strengthen the inhibition of green finance on carbon emissions, and the regulatory effects of different types of environmental regulatory tools may be heterogeneous.

3.3 Regulatory effect of environmental regulation policy

Green finance can accelerate industrial low-carbon transformation and reduce carbon emissions by guiding the allocation of financial resources, increasing financing channels for enterprises, transmitting green development signals, and stimulating enterprises' green technology research and development power (Jiang et al., 2022; Zhang et al., 2023). However, due to the early introduction of green finance in China, a perfect legal system has not yet been formed. In order to break through this dilemma, it is urgent to strengthen the guarantee of green financial system and prevent the emergence of market failure. Green finance emphasizes that production and operation activities should follow the laws of eco-economy, save resources and energy, and reduce ecological environmental pollution, which inevitably requires enterprises to use various green technologies such as eco-technology, pollution control and prevention, and recycling to promote process innovation, management optimization, and equipment upgrading, and form an industrial green supply chain, thereby reducing carbon emissions in the production process. However, in this process, the long research and development cycle of green innovation technology, high investment cost, uncertainty of rate of return on capital and other factors are very likely to induce enterprises to take lower-cost and inefficient "green washing" and terminal treatment to cover up the negative environmental externalities of production activities, thus failing to truly reduce the carbon emissions of enterprises.

Therefore, environmental regulatory tools can provide institutional guarantee in the process of green finance affecting carbon emissions and strengthen the effect of carbon emission reduction. Specifically, firstly, environmental regulation, as policy support, can directly improve the efficiency of fund allocation of green finance, build a green capital flow carrier, and form a new model of environmental protection policy system and green finance to support low-carbon development, thus guiding social idle capital

to flow into the field of green production and breaking the limitation of single green investment (Cui et al., 2022; Yan et al., 2023b). Second, with the continuous improvement of the environmental regulatory policy system, the government will force enterprises to meet the specified environmental standards or immediately shut down for rectification, so that they will no longer choose terminal treatment technologies that are easy to imitate and low-cost to avoid administrative punishment, and will force enterprises to adopt standardized green production technologies, speed up the development of new energy, green innovation and green industrial structure transformation, and then control carbon dioxide emissions from the source (Tong et al., 2022; Li et al., 2023).

Based on the above analysis, the article puts forward the following assumptions:

Hypothesis 3. Environmental regulatory policies may have a regulatory effect in the process of green finance affecting carbon emissions.

4 Research design and data sources

4.1 Variable selection

4.1.1 Explained variable

Carbon dioxide emissions mainly come from the respiration of animals, plants and microorganisms in nature, the early decomposition of carbonate minerals and the burning of fossil fuels by human beings. However, in the actual measurement process, due to the inaccuracy of the estimation model, the calculation error of carbon emission factors, the unavailability of original data and the existence of unknown carbon sources, it is easy to cause errors in the estimation of carbon emissions from carbon sources.

In order to obtain more accurate data of carbon emissions, this paper considers the following aspects: (1) Carbon dioxide emissions mainly come from the energy consumption in the process of thermal power generation and heating in the process of terminal consumption and energy processing conversion, and other energy processing conversion processes (such as coal preparation, coking, oil refining and coal-to-liquid production, gas making, natural gas liquefaction, etc.) and transportation and distribution losses are not considered; (2) There are great differences in energy consumption structure and application degree of energy-saving and emission-reduction technologies in different regions of China, which leads to great differences in carbon emission factors of electricity and heat in different regions. In order to calculate the carbon dioxide emissions of regional electricity and heat more accurately, 17 energy varieties with relatively stable emission factors, such as raw coal, cleaned coal, other washed coal, briquette, coke, coke oven gas, other gas, other coking products, crude oil, gasoline, kerosene, diesel oil, fuel oil and natural gas, are selected for indirect calculation. (3) Regional power includes both local thermal power generation and external power supply. Therefore, in the process of calculating the carbon emissions of regional power, the carbon emissions transferred from other provinces (autonomous regions and municipalities) should be deducted after calculating the carbon emissions transferred from this province (autonomous regions and municipalities) according to the principle of production place.

In view of this, this paper uses the practices of Wang and Geng (2015), Song et al. (2021), and Wang et al. (2021), for reference, and combines the characteristics of China's regional energy statistics to calculate the regional carbon emissions. The calculation formula is shown in Eq 1:

$$C_{it} = \frac{44}{12} \times \left(\sum_{j=1}^{17} Z_{ijt} + \sum_{j=1}^{17} D_{ijt} + \sum_{j=1}^{17} R_{ijt} + O_{it} - I_{it} \right)$$
$$= \frac{44}{12} \times \left(\begin{array}{l} \sum_{j=1}^{17} ZE_{ijt} \times \delta Z_{ijt} \times \eta Z_{ijt} + \sum_{j=1}^{17} DE_{ijt} \times \delta D_{ijt} \times \eta D_{ijt} \\ + \sum_{j=1}^{17} RE_{ijt} \times \delta R_{ijt} \times \eta R_{ijt} + (OE_{it} - IE_{it}) \times \delta E_t \times \eta E_t \end{array} \right) \quad (1)$$

Among them, C_{it} represents the carbon dioxide emissions of i province in the t year; Z_{ijt}, D_{ijt} and R_{ijt} respectively represent the carbon emissions of thermal power generation and heating in the terminal energy consumption and energy processing conversion in each province in the t year, and O_{it} and I_{it} respectively represent the power transfer-out and transfer-in of i province in the t year; ZE_{ijt}, DE_{ijt} and RE_{ijt} respectively represent the J-type terminal energy consumption, thermal power generation energy consumption and heating energy consumption in energy processing and conversion in i province in the t year; δZ_{ijt}, δD_{ijt} and δR_{ijt} are the corresponding conversion coefficients of energy consumption standards, and ηZ_{ijt}, ηD_{ijt} and ηR_{ijt} are the corresponding carbon emission coefficients of energy consumption; OE_{it}, IE_{it} represent the electric power transferred from the province (autonomous region, municipality) and transferred from other provinces (autonomous regions, municipalities) in the t year respectively, and δE_t, ηE_t represent the conversion coefficient and carbon emission coefficient of standard electric power consumption in China in the t year.

It should be noted that the conversion coefficient of standard quantity of energy consumption in the process of terminal energy consumption, thermal power generation and heating and the conversion coefficient of standard quantity of electric power transferred in and out of regions are all expressed as the ratio of standard quantity to physical quantity of certain energy consumption, that is, as shown in Eqs 2–6:

$$\delta Z_{ijt} = \frac{ZEB_{jt}}{ZES_{jt}} \quad (2)$$

$$\delta D_{ijt} = \frac{DEB_{jt}}{DES_{jt}} \quad (3)$$

$$\delta R_{ijt} = \frac{REB_{jt}}{RES_{jt}} \quad (4)$$

$$\delta E_{it} = \frac{ZEEB_t}{ZEES_t} \quad (5)$$

$$\eta E_{it} = \frac{\frac{44}{12} \times \sum_{j=1}^{17} DE_{jt} \times \delta D_{jt} \times \eta D_{jt}}{ZEEB_t} \quad (6)$$

4.1.2 Core explanatory variable

Green finance. As a financial model committed to green and sustainable development, it can not only effectively coordinate the relationship between ecology and finance, but also guide the optimal allocation of capital, environmental resources and social resources.

TABLE 1 Evaluation index system of green finance development index.

Primary index	Secondary index	Index definition	Attribute
Green credit	Interest proportion of six high energy-consuming industries	Proportion of industrial interest in six high-energy-consuming industries to total industrial interest expenditure	-
	Proportion of green credit	Proportion of green credit balance of financial institutions to total loans of major financial institutions	+
Green securities	Share of A-share market value of environmental protection enterprises	Proportion of A-share market value of environmental protection enterprises to the total A-share market value	+
Green insurance	Proportion of agricultural insurance scale	Proportion of A-share market value of environmental protection enterprises to the total A-share market value	+
	Agricultural insurance payout ratio	Proportion of agricultural insurance expenditure to total insurance income	+
Green investment	Proportion of public expenditure on energy conservation and environmental protection	Proportion of fiscal expenditure on energy conservation and environmental protection to total public financial expenditure	+
	Proportion of investment in environmental pollution control	Proportion of investment in environmental pollution control to regional GDP	+

In 2016, seven departments, including the People's Bank of China and the China Securities Regulatory Commission, jointly issued the Guiding Opinions on Building a Green Financial System, requiring financial instruments such as green credit, green bonds, green insurance and green stock index and related policies to support the development of green and low-carbon economy. In view of this, based on the completeness of indicator setting and the availability of data, this paper draws lessons from the practices of Chen et al. (2021), Feng et al. (2023), and Lin et al. (2023), and constructs the evaluation index system of China's green financial development level from the four dimensions of green credit, green securities, green insurance and green investment. The specific indicators are shown in Table 1.

In the process of constructing the green financial development index, the difference in the distribution of the weights of each subdivision index will directly affect the reliability and accuracy of the evaluation results. Entropy weight method objectively weights the indicators by the amount of information provided by the observed values of each indicator, which better avoids the result error caused by human factors. Therefore, this paper uses entropy weight method to weight the internal indicators of each dimension, and the specific calculation steps are as follows:

(1) The forward and reverse indicators are dimensionless. The treatment method is as follows:

$$x_{ij}^{+} = \frac{x_{ij} - x_{i\,min}}{x_{i\,max} - x_{i\,min}} \tag{7}$$

$$x_{ij}^{-} = \frac{x_{i\,max} - x_{ij}}{x_{i\,max} - x_{i\,min}} \tag{8}$$

Among them, $x_{i\,max}$ represents the maximum value of the i index, $x_{i\,min}$ represents the minimum value of the i index, and x_{ij} represents the index value of the year of the I index.

(2) Construct an evaluation matrix. Assume that the dimension of the M-year green financial index of a province to be measured contains n indicators x_{ij}, so the original coefficient matrix A is shown in Eq 9:

$$A = \begin{pmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{pmatrix} \tag{9}$$

Where m represents the number of evaluation indicators and n represents the number of years of evaluation indicators.

(3) Calculate the entropy value of the j index. Considering that it needs to be logarithmized when calculating the information entropy, in order to avoid the situation that the standardized index value is zero, this paper refers to the practice of Zhang et al. (2014), and only shifts the initial standardized data by 0.01 unit to the right, then the information entropy e_j of the j-th index is expressed as:

$$e_j = -\frac{1}{lnn}\sum_{i=1}^{n}\left(f_{ij}\, ln\, f_{ij}\right) \tag{10}$$

$$f_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \tag{11}$$

(4) Calculate the coefficient of difference of the j index:

$$g_j = 1 - e_j \tag{12}$$

(5) Calculate the weight ω_j of each index:

$$\omega_j = \frac{g_j}{\sum_{j=1}^{n} g_j} \tag{13}$$

(6) Calculate the development index of green finance in i province:

$$S_i = \sum_{j=1}^{n} \omega_j f_{ij} \tag{14}$$

4.1.3 Mechanism variables

Environmental regulation. At present, there is no uniform regulation on the measurement of environmental regulation in academic circles.

TABLE 2 Descriptive statistics of variables.

	Variable name	Abbreviation	Observation	Mean	Standard deviation	Min	Max
Explained variable	Carbon dioxide emission	Carbon	540	10.1622	0.7723	8.1645	14.0752
Explanatory variable	Green finance	GF	540	0.3722	0.1490	0.0964	0.8372
Regulated variable	Command-controlled environmental regulation	CER	540	8.4516	1.7145	6.4772	10.2449
	Market-driven environmental regulation	MER	540	3.5699	1.3016	1.3917	12.6893
	Public-participation environmental regulation	PER	540	2.0514	1.0539	1.5287	9.7201
Control variable	Economic development level	EDL	540	10.4764	0.5099	8.2103	12.0094
	Urbanization rate	UR	540	0.5703	0.1431	0.2942	0.8960
	Foreign direct investment	FDI	540	0.6531	0.3912	0.5898	1.0127
	Industrialization degree	ID	540	0.8873	0.0619	0.6207	1.1358
	Government intervention degree	GID	540	1.5407	0.3308	1.3273	4.0727

Some scholars measure the level of environmental regulation by using indicators such as the control effect of industrial "three wastes", the investment in environmental pollution control and the comprehensive index of environmental regulation. Based on the availability of data and the integrity of indicators, this paper further divides environmental regulation tools into command-controlled environmental regulation, market-driven environmental regulation and public-participation environmental regulation with reference to the practices of Xiao et al. (2021), Chen et al. (2022) and Zhang et al. (2023). Among them, command-controlled environmental regulations are laws and regulations formulated by legislative or administrative departments, which directly affect polluters to make environmentally friendly choices, and are mainly reflected in the pollutant discharge and disposal of enterprises due to regulatory standards. Therefore, this paper selects the proportion of "three simultaneities" environmental protection investment in each province (autonomous region and municipality) to the regional GDP to characterize it; Market-driven environmental regulation aims to guide enterprises' pollutant discharge behavior with the help of market signals, so that the overall pollution situation of society tends to be controlled and optimized, which is mainly reflected in encouraging economic entities to reduce their own pollutant discharge level through tradable pollutant discharge permits or pollutant discharge taxes and fees. Therefore, this paper selects the proportion of sewage collection, pollution control investment and resource tax in local fiscal revenue in various provinces (autonomous regions and municipalities) to measure; The core idea of public-participation environmental regulation is that the public and non-profit environmental protection organizations can complain to the relevant departments or disclose the pollution behavior of enterprises by public opinion, which will exert supervision pressure on polluting enterprises, so that enterprises can take the initiative to assume social responsibility for environmental protection. Therefore, this paper selects the sum of letters from the public on environmental issues in various provinces (autonomous regions and municipalities), the number of visiting batches and the number of environmental protection news releases reported by party and government organs as proxy variables.

4.1.4 Control variable

In order to minimize the error caused by the omission of important variables to the causal inference of the model, this paper selects the following control variables according to the research perspective of existing literature: economic development level. Environmental Kuznets Curve (EKC) shows that the relationship between economic growth and carbon emissions is inverted U-shaped, and higher GDP growth in the short term means more carbon dioxide emissions. In view of this, this paper refers to the practice of Zhao et al. (2022), and chooses the *per capita* GDP value after logarithmic processing to measure it; Urbanization rate. The improvement of urbanization level will accelerate the agglomeration of factors and industries, improve the utilization efficiency and scientific and technological level of public facilities, improve production efficiency, increase the utilization of clean energy, and thus reduce carbon emissions. In view of this, this paper refers to the practice of Li et al. (2023a), and chooses the proportion of urban population to the total population to represent it; Foreign direct investment. Foreign direct investment can transfer industries with high energy consumption and high emissions to China, resulting in a "pollution paradise" effect. But at the same time, the green technology introduction and technology spillover it brings will have a "pollution halo" effect. In view of this, this paper refers to the practice of Li et al. (2023b), and selects the actual utilization of foreign direct investment and the investment amount converted according to the average exchange rate of RMB against the US dollar over the years to represent it; Industrialization degree. The promotion of industrialization will inevitably generate huge demand for labor, materials, investment and other resources, thus aggravating the level of carbon emissions pollution. In view of this, this paper refers to the practice of Hu et al. (2023), and

selects the proportion of the added value of the secondary industry in GDP to measure it; Government intervention degree. The government's intervention in the financial market tends to distort the bank's credit behavior and crowd out green enterprises with long R&D cycle and low short-term return rate, thus increasing carbon dioxide emissions. In view of this, this paper refers to the practice of Wu et al. (2024), and adopts the proportion of expenditure in local government budget to GDP.

4.2 Model setting

In order to verify the above research hypothesis and mechanism, this part uses mathematical statistical model to verify it. According to the definition and selection of explained variables, core explanatory variables and control variables, the following benchmark econometric models are constructed:

$$Carbon_{it} = a_0 + a_1 GF_{it} + a_2 \sum_{i=1}^{6} Control_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (15)$$

In Eq 15, the subscripts i and t denote individuals and years respectively, α denotes coefficients to be estimated, a_0 denotes constant terms, *Control* denotes information sets, that is, all control variables except the core explanatory variables, λ_i denotes individual fixed effects, μ_t denotes time fixed effects, and ε_{it} denotes random disturbance terms subject to white noise processes. In the actual fitting calculation process, in order to slow down the influence of heteroscedasticity and reduce the data level of variables, all variables are logarithmically transformed in this paper.

Considering that there may be a nonlinear relationship between green finance and carbon emissions, this paper brings the square term GF_{it}^2 of green finance index into the model framework, and to avoid collinearity, GF_{it-1} is decentralized and then multiplied by square, and the following econometric model is established:

$$Carbon_{it} = a_0 + a_1 GF_{it} + a_2 GF_{it}^2 + a_3 \sum_{i=1}^{6} Control_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (16)$$

In addition, in order to verify the regulatory effect of environmental regulation tools in the process of green finance affecting carbon emissions, this paper sets the following econometric equation:

$$Carbon_{it} = a_0 + a_1 GF_{it} + a_2 ER_{jt} + a_3 \left(GF_{it} \times ER_{jt}\right) + a_4 \sum_{i=1}^{6} Control_{it} + \lambda_i + \mu_t + \varepsilon_{it} \quad (17)$$

Among them, $j = 1, 2, 3$ correspond to command-controlled environmental regulation, market-driven environmental regulation and public-participation environmental regulation respectively.

4.3 Data source

According to the principle of data availability, this paper selects the panel data of 30 provinces in China from 2004 to 2021 (except Tibet, Hong Kong, Macao and Taiwan) as the research sample. The original data of all variables mainly come from China Statistical Yearbook, China Energy Statistical Yearbook, China Industrial Statistical Yearbook, China Environmental Statistical Yearbook, China Insurance Yearbook, China Carbon Accounting (CEADs) database, Easy Professional Superior (EPS) database and statistical yearbooks of various provinces and cities. For a few missing values, LaGrange interpolation polynomial is used to complete them. The definitions and statistical characteristics of main variables are shown in the Table 2. From the statistical results, we can find that the average value of green finance is 0.3722 and the standard deviation is 0.1490, which indicates that there is no big difference in the development level of green finance among different provinces. However, the standard deviation of carbon emissions reached 0.7723, and the difference between the maximum value and the minimum value was 5.9107, indicating that there was an obvious gap in carbon emissions among provinces.

TABLE 3 Results of variable correlation analysis.

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Carbon	1.000						
GF	0.468	1.000					
EDL	0.472	0.036	1.000				
UR	0.365	−0.120	0.643	1.000			
FDI	0.347	0.015	0.176	0.160	1.000		
ID	0.370	0.249	0.564	0.557	0.003	1.000	
GID	0.137	0.077	−0.065	0.283	−0.279	0.032	1.000

5 Analysis of empirical results

5.1 Variable correlation test

Before establishing the model for empirical analysis, it is necessary to test the correlation of each variable first, so as to avoid the deviation of the estimation of the model due to the high correlation between variables. In this paper, Pearson correlation coefficient and variance expansion factor are used to judge the correlation between variables, and the test results are shown in the Table 3. It is not difficult to see that there is a certain degree of correlation between the variables, but the values are all less than 0.7, which does not constitute a strong correlation.

Besides, in the process of verifying the carbon emission reduction effect of green finance, this paper selects more control variables in order to obtain unbiased estimation as much as possible. In order to prevent multicollinearity from making variable significance and parameter estimation lose practical significance, it is necessary to carry out multicollinearity test. According to the test results in Table 4, the largest variance expansion factor is 4.80 of the industrialization degree (ID), and the average variance expansion factor is 3.25. The VIF of the other variables is also less than the critical standard of 10. Therefore, it can be concluded that there is no multicollinearity problem in the econometric model constructed in this paper, and the next regression analysis can be carried out.

TABLE 4 Multiple collinearity test results.

Variable	VIF	1/VIF
ID	4.80	0.208481
EDL	4.40	0.227508
GF	3.06	0.326683
FDI	2.83	0.326683
UR	2.21	0.452472
GID	2.19	0.455777
Mean VIF	3.25	

5.2 Analysis of benchmark regression results

The commonly used panel fitting models include the pooled ordinary least square method (POLS), random effects model (RE), and fixed effects model (FE). The specific model that is most suitable for the sample data in this article needs to be distinguished using F-test, LM test, and Hausman test. The test results show that the F statistic of likelihood ratio test is 25.66, and that of Hausman test is 46.08, both of which are significant at 1% significance level. Based on this, this paper adopts two-way fixed effect model as the benchmark regression model for subsequent empirical test, namely, fixed individual effect and time effect. At the same time, in order to eliminate the interference of heteroscedasticity, sequence correlation, and cross-sectional correlation on the regression results, the article mainly uses Driscoll-Kraay standard error to address it, and uses feasible generalized least squares (FGLS) for auxiliary verification. The specific estimated results are shown in Table 5.

Considering the robustness of the model, this paper still reports the estimation results of POLS and RE models. It can be seen from the Table 5 that the average estimation coefficient of green finance is -0.328 and is significant at the significance level of 1%, which indicates that green finance has a significant inhibitory effect on carbon emissions. The possible reasons behind it are as follows: on the one hand, the development of green finance has a "subsidy effect" on environmental protection technology innovation, that is, it provides diversified risk compensation and guarantee mechanisms for green technology innovation by giving play to risk management functions, and the driver also realizes low-carbon transformation. At the same time, under the guidance of green development, financial institutions will provide financing facilities for enterprises that adopt cleaner production technologies, save energy and reduce emissions, promote the transfer and reorganization of production factors such as capital, labor and technology, and alleviate the mismatch of resources, thus accelerating the green transformation and upgrading of enterprises and making it possible to decouple carbon emissions from economic growth; On the other hand, the development of green finance has a "crowding-out effect" through the pricing of financial products, that is, financial institutions increase the financing cost of high-emission enterprises by incorporating the environmental cost of carbon emissions into the prices of financial products, forcing them to upgrade their production processes or withdraw from the market. According to the results of green finance index, the fitting coefficients of GF and GF (-1) are -0.424 and -0.209, respectively, and they have passed the 1% and 5% level significance tests, indicating that the rapid development of green finance is an important means to reduce pollution and carbon, but the carbon emission reduction effect of green finance has obvious time lag effect, and after considering heteroscedasticity, autocorrelation and cross-section correlation, FGLS estimation is made. This conclusion is similar to the research results of Zhang et al. (2023) and Lin et al. (2023), that is, with the deepening influence of economic factors such as economic development level and urbanization, the effect of green finance on carbon emissions is limited. The possible reasons are as follows: First, China's green finance started late, and there are some problems in the development process, such as unclear path plan and vague objectives, and most of the relevant policy documents are principled and programmatic documents, lacking specific and effective implementation measures, which makes the supply of green finance unable to accurately correspond to the development needs of low-carbon economy, thus leading financial institutions to fail to capture the capital demand generated by carbon emission reduction in time, which hinders the progress of green transformation and development of enterprises; Second, green financial projects usually take a long

TABLE 5 Benchmark regression results.

Variable	POLS	RE	FE	FGLS	FE	FGLS
GF	−0.245*** (−4.54)	−0.095*** (−9.08)	−0.328*** (−4.35)	−0.631*** (−2.61)	−0.424*** (−5.59)	−0.413*** (−3.48)
GF (−1)					−0.209** (−2.37)	−0.094*** (−3.12)
EDL	0.148** (2.35)	0.277*** (2.59)	0.395** (2.01)	0.346* (1.77)	0.391** (2.11)	0.280* (1.95)
UR	−0.180*** (−4.58)	−0.168*** (−4.67)	−0.209* (−1.87)	−0.326** (−2.28)	−0.275** (−2.19)	−0.271* (−1.73)
FDI	−0.029*** (−6.73)	−0.029*** (−2.98)	−0.031** (−2.14)	−0.017 (−1.33)	−0.069*** (−3.19)	−1.028*** (−4.37)
ID	0.085*** (2.58)	0.295* (1.66)	0.156 (0.79)	0.266* (1.94)	0.150* (1.74)	0.219*** (2.88)
GID	0.765** (2.24)	0.291 (0.37)	1.162** (2.13)	1.491*** (2.75)	1.036** (2.12)	0.472 (0.55)
Constant	2.687*** (2.67)	2.639** (2.34)	2.722** (2.41)	1.125* (1.83)	1.484** (1.99)	1.008* (1.65)
R^2	0.7328	0.8012	0.8305	0.8914	0.8817	0.8736

Note: *, ** and ***, respectively, indicate significant at 10%, 5% and 1% significance levels; T statistics are in brackets.

time to implement and have obvious positive externalities, which leads to high risks and cannot provide matching high returns. In order to realize the low-carbon economy, a large number of enterprises enter the new energy market in a short time, which leads to the decline of core competitiveness and low profit rate of new energy enterprises, and often faces practical difficulties such as the extension of financing projects, the oversaturation of the market and the difficulty in realizing products. Finally, the carbon emission reduction effect of green finance will be reflected after a certain period of time.

5.3 Endogenous treatment

Usually, endogenous problems involve omission of important variables, measurement deviation and mutual causality. Although in this paper, when considering the relationship between green finance and carbon emissions, more control variables are selected to alleviate the endogenous problems caused by missing variables and measurement errors, the model setting is still threatened by the mutual causal endogenous problems between them. In view of this, considering the rigor of the conclusion, this paper chooses the following two ways to eliminate the possible endogenous problems: one is to refer to the practice of Xie et al. (2023), using the product of the lag term (GF (-1)) and the difference term (ΔGF) of green finance as a tool variable for two-stage least squares estimation (2SLS); Secondly, the lag term of the explained variable is included in the model, and a dynamic panel model is constructed to fit the data. On the basis of differential generalized moment estimation, Blundell and Bond improved the system generalized moment estimation method (SYS-GMM), which made up the deficiency of differential GMM (Blundell et al., 1998). At the same time, because the two-step SYS-GMM is easy to cause the parameter values to be seriously underestimated in small samples, and then the variables are too significant, WC-robust estimation method is used to correct this. The specific results are shown in Table 6.

As can be seen from Table 6, each model has passed the unrecognizable test, weak instrumental variable test and over-identification test, and it shows that the carbon emission reduction effect of green finance still exists after considering endogenous problems, and even the estimation coefficient has increased. Therefore, after eliminating the possible endogenous problems, the impact of green finance on carbon emissions still supports the conclusions in the benchmark regression analysis. In addition, the estimation results of SYS-GMM and DFF-GMM models also show that the lag term of the explained variables is significantly positive, indicating that the current carbon emissions will be affected by the total carbon emissions in the previous period, and there is a typical inertia effect.

5.4 Robustness test

In order to verify the robustness and reliability of the benchmark regression estimation results, this paper uses the following three methods to verify:

First, tail-shrinking treatment. In order to prevent outliers from causing errors in regression results, such as economic shocks or major natural disasters during the epidemic period, all kinds of enterprises are faced with huge competitive risks, prolonged financing projects, over-saturation of the market and difficulties in realizing products. Therefore, all continuous variables are truncated by 1% up and down, and then re-estimated by fixed effect model.

Second, change the sample size. Because Chinese municipalities (Beijing, Tianjin, Shanghai, Chongqing) enjoy central policy support and tax preference in financial development, and local financial institutions store larger transaction data and customer information, which is heterogeneous with other provinces, this paper excludes them and re-estimates them by using fixed effect model.

Third, replace the explained variables. The input-output process of energy is complex. Taking industrial production as an example, the production of raw materials such as cement, lime and glass will also produce carbon emissions. Therefore, there may be a certain measurement error between the carbon emissions calculated based on fossil energy consumption and the actual carbon emissions in the region, which will have a certain impact on the model estimation results. In view of this, this paper replaces the explained variable with the carbon emissions of provinces published by China Carbon Accounting Database (CEADs), and re-estimates the model.

From the robustness results (Table 6), all three methods show that green finance has a significant inhibitory effect on carbon emissions, and the level of significance has not changed significantly, which fully shows that the benchmark regression results are reliable and robust, that is, there is an obvious negative relationship between green finance and carbon emissions.

5.5 Further analysis

5.5.1 Heterogeneity test

5.5.1.1 Heterogeneity test of green finance fractal dimension

The development of green finance is not monotonous and independent, but towards green credit, green insurance, green securities and green investment, so it is necessary to analyze the structural effects of green finance on carbon emissions. It is not difficult to find from Table 7 that green credit, green insurance and green investment have obvious inhibitory effects on carbon emissions at a significant level of 1%, with coefficients of -0.366, -0.173 and -0.281 respectively. However, the carbon emission reduction effect of green securities has not passed the significant test. With the continuous release of relevant policies such as Statistical System of Green Credit and Key Evaluation Indicators of Green Credit Implementation, China's green credit market system has been gradually improved. Therefore, in the process of developing green finance, we can quickly and reasonably allocate funds to areas such as environmental protection, energy conservation and emission reduction, meet the financing needs of environmental protection enterprises, and innovate green products and services. At the same time, by reducing the credit line for enterprises with high pollution, high emission and high energy consumption, the "three high" enterprises are forced to accelerate the green transformation and reduce carbon emissions. In addition,

TABLE 6 Endogenous treatment and robustness test results.

Variable	Endogenous treatment			Robustness test		
	2SLS	SYS-GMM	DFF-GMM	Tail shrinking treatment	Changing sample size	Replacing interpreted variables
Lag term		0.277*** (7.24)	0.305*** (8.84)			
GF	−0.386*** (−5.90)	−0.412*** (−3.68)	−0.471*** (−2.79)	−0.212*** (−3.73)	−0.072** (−2.03)	−0.099** (−2.47)
Control variable	Control	Control	Control	Control	Control	Control
Over-identification test	0.264	0.343	0.165			
Insufficient recognition test	186.952***					
Weak instrumental variable test	383.582					
AR (1)		0.074	0.030			
AR (2)		0.258	0.365			
Time effect				Control	Control	Control
Individual effect				Control	Control	Control
R^2	0.813			0.843	0.794	0.823

Note: *, ** and ***, respectively, indicate significant at 10%, 5% and 1% significance levels; T statistics are in brackets.

TABLE 7 Results of fractal heterogeneity test.

Variable	Green credit	Green securities	Green insurance	Green investment
GF	−0.366*** (−3.56)	0.052 (−0.17)	−0.173*** (−2.90)	−0.281*** (−3.37)
Control variable	Control	Control	Control	Control
Time effect	Control	Control	Control	Control
Individual effect	Control	Control	Control	Control
R^2	0.823	0.607	0.849	0.758

Note: *, ** and ***, respectively, indicate significant at 10%, 5% and 1% significance levels; T statistics are in brackets.

the carbon emission reduction effect of green securities has not yet appeared, which may be due to the short official issuance time of green securities in China, a series of obstacles such as small overall issuance scale, imperfect system and time delay in signal transmission in the securities market.

5.5.1.2 Heterogeneity test of sub-regions

Because the sample involves 30 provinces in China (except Tibet, Hong Kong, Macao and Taiwan), the regional span is large, and there are differences in green financial reform and innovation policies, resource endowments, location advantages, economic development levels and other factors among provinces, resulting in certain heterogeneity in their respective green financial development levels and industrial ecological environment levels. At the same time, with the continuous acceleration of urbanization, the carbon emissions between neighboring provinces are spatially dependent. In view of this, referring to the research results of China Physical Geography and Guo et al. (2023), this paper divides the geographical region of China into eastern region, central region, western region and northeast region, so as to further investigate the differences in the impact of green finance on carbon emissions. Among them, each region contains provinces as shown in the table 8.

From Table 9, it can be found that whether control variables are added or not, green finance in different regions has a significant inhibitory effect on carbon emissions, but the difference is that the effect is slightly different. Among them, the effect of green finance in the eastern region is the most obvious, and the regression coefficient is -0.274. The reason is that, because of its targeted marketing function and its natural green attribute, green finance can not only reduce the moral hazard and adverse selection caused by information asymmetry, but also provide sufficient funds for green business activities accurately but conditionally, promote high-quality production factors to flow into environmental protection projects and guide the green transformation of traditional industries. Beijing, Tianjin, the Yangtze River Delta and other regions are rich in natural resources and geographical advantages, and the level of green finance is far ahead of other regions. There are many kinds of green financial instruments, which make the production of various industries have financial guarantee,

TABLE 8 Provinces included in each region.

Region	Included provinces
Eastern Region	Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan
Central Region	Shanxi, Anhui, Jiangxi, Henan, Hubei, Hunan
Western Region	Inner Mongolia Autonomous Region, Guangxi Zhuang Autonomous Region, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia Hui Autonomous Region, Xinjiang Uygur Autonomous Region
Northeast Region	Liaoning, Jilin, Heilongjiang

TABLE 9 Results of regional heterogeneity test.

Variable	Eastern region		Central region		Western region		Northeast region	
GF	−0.708** (−2.37)	−0.274*** (−4.61)	−0.836*** (−3.79)	−0.193* (−1.66)	−0.436** (−2.05)	−0.031** (−1.99)	−0.556*** (−3.06)	−0.118** (−2.03)
EDL		0.209*** (3.70)		0.077** (1.98)		0.191*** (2.71)		0.164*** (3.78)
UR		−0.047*** (−4.67)		−0.148* (−1.65)		−0.075** (−2.06)		−0.161*** (−4.67)
FDI		−0.010* (−1.67)		−0.028*** (−5.73)		−0.009*** (−4.07)		−0.015** (−2.28)
ID		0.339** (2.16)		0.355** (2.48)		0.288* (1.81)		0.290** (2.46)
GID		0.248 (0.35)		0.472* (1.95)		0.336 (0.12)		0.205* (1.67)
Constant		2.481*** (4.79)		3.008* (1.69)		2.727*** (3.18)		1.825** (2.47)
Time effect	Control	Control	Control	Control	Control	Control	Control	Control
Individual effect	Control	Control	Control	Control	Control	Control	Control	Control
Number of provinces	10	10	6	6	11	11	3	3

Note: *, ** and ***, respectively, indicate significant at 10%, 5% and 1% significance levels; T statistics are in brackets.

and efficient, low-carbon and green business models are widely selected, thus promoting the green development of industries and reducing carbon dioxide emissions. However, in order to promote the economic development of the western region, China has put forward a series of policies focusing on the strategy of "developing the western region" and encouraged some industries in the eastern region to move to the west, which to some extent strengthened the proportion of heavy and chemical industries in the western region and increased the total carbon emissions in the western region. In addition, the dilemma of "economy-environment" zero-sum game leads to the neglect of the development of green finance in the western region with low industrial level and far from the technological frontier, which leads to the lack of first-Mover advantage in promoting carbon emission reduction.

5.5.2 Analysis of regulatory effect

In order to reveal whether the environmental regulation policy plays a regulatory role in the process of green finance affecting carbon emissions, based on the above equation and its related principles, the benchmark regression model is used for fitting calculation. The specific inspection results are shown in Table 10.

It is not difficult to see from the Table 10 that both the command-and-control environmental regulation tools and the public participation environmental regulation tools have a significant negative impact on carbon emissions, and their fitting coefficients are -0.097 and -0.131, respectively, and they have passed the significance test at 1% level. At the same time, the product of these two kinds of environmental regulation tools and green finance index has a significant positive impact on carbon emissions, which shows that command-and-control environmental regulation and public participation environmental regulation have a positive regulatory effect on the carbon emission reduction effect of green finance. For command-and-control environmental regulation tools, the strengthening of its regulation will directly reduce the production scale of high-emission enterprises, and financial institutions will also reduce their financial support and even force them to withdraw from the market. As for the tools of public participation in environmental regulation, the pressure and supervision of the public on the production activities of enterprises will continue to increase with the enhancement of environmental awareness, which will directly reverse the low-cost green-washing and end-treatment behaviors of enterprises and reduce carbon emissions. Therefore, these two kinds of environmental regulation tools both restrain carbon emissions to a certain extent, worsen the financing environment of high-emission enterprises, reduce their production scale and even force them to invest in green low-carbon technologies, realize the green transformation of production methods and strengthen the carbon emission reduction effect of green financial development.

TABLE 10 Test results of regulatory effect.

Variable	(1)	(2)	(3)
GF	−0.291*** (−9.82)	−0.457*** (−5.18)	−0.166** (−2.13)
CER	−0.097*** (−4.20)		
CER*GF	0.359*** (9.41)		
MER		−0.104 (−0.28)	
MER*GF		0.382 (0.74)	
PER			−0.131*** (−3.16)
PER*GF			0.124** (2.35)
Control variable	Control	Control	Control
Time effect	Control	Control	Control
Individual effect	Control	Control	Control
Sample size	540	540	540
R^2	0.8283	0.7332	0.8126

In addition, market-driven environmental regulation tools have not significantly inhibited carbon emissions, and have not shown a regulatory effect on the carbon emission reduction effect of green finance. The reason may be that the market-driven environmental regulation tools rely on the market regulation mechanism. Once the market mechanism is not perfect, especially the carbon emission trading license market is not mature and the environmental tax rates are inconsistent in different places, the market-driven environmental regulation tools cannot promote technological innovation, but may breed the phenomenon of "environmental rent-seeking" and increase the environmental governance burden of enterprises. At the same time, financial institutions' loans to enterprises are mainly based on the quality of their mortgaged assets, rather than the green degree of their production methods. In addition, there is no effective linkage between themselves and environmental protection departments, and they cannot obtain relevant environmental punishment information in time, which leads to the failure of market-driven environmental regulation tools to effectively enhance the carbon emission reduction effect of green financial development.

6 Conclusion and policy recommendations

6.1 Conclusion

By systematically combing the related theories of green finance and environmental regulation affecting carbon emissions, as well as the regulatory effect mechanism of heterogeneous environmental regulation, the evaluation index system of China provincial green finance development index is constructed, and the green finance level of 30 provinces in China from 2004 to 2021 is calculated and evaluated by entropy weight method. Then, a series of mathematical statistical models are used to verify the relationship among green finance, environmental regulation and carbon emissions. This paper obtained several results. First, the development of green finance has a significant inhibitory effect on carbon emissions, and there is a certain time lag effect. This conclusion still holds after a series of robustness tests and endogenous treatment. Second, from the results of regional heterogeneity, with its unique geographical advantages and economic characteristics, the carbon emission reduction effect of green finance is more prominent in the eastern region. This conclusion is similar to that of Bao et al. (2022) and Wu et al. (2023), and both indicate the particularity of the western region in the process of industrialization and modernization in China, which is hindered by the serious solidification of urban structure. From the sub-dimension of green financial development, green credit, green investment and green insurance all have carbon emission reduction effects, but the only difference is that the inhibition effect is slightly different. Third, command-controlled environmental regulation tools and public participation environmental regulation tools have a positive regulatory effect on the carbon emission reduction effect of green finance, while market-driven environmental regulation tools cannot effectively enhance the carbon emission reduction effect of green finance development.

6.2 Policy recommendations

In view of this, this paper puts forward the following policy suggestions:

(1) Attach great importance to the construction of green financial policy system and improve the inclusiveness, coverage and accuracy of financial services. First of all, the government should gradually establish and improve laws and regulations related to green finance, establish green financial standards from the legislative level, simplify green financing processes, and rationalize green financing procedures, so as to give full play to the financial subsidies and incentives for low-carbon projects and promote the diversified development of green financial instruments. Secondly, we should specify different standards according to different production projects, strictly control the financial support for high-pollution and high-emission industries, and increase the transaction costs of high-energy-consuming enterprises. Thirdly, further improve the green financial supervision system, form a standardized and transparent information disclosure system for green financial supervision and corporate environmental pollution, increase penalties for environmental pollution violations, and improve the return rate of green finance. Finally, accelerating the improvement of the characteristic service standards, general basic standards and credit rating standards of green financial products. At the same time, enterprises rely on the platform of professional institutions to strengthen the integration and upgrading of financial technology and digital technology, increase their application in environmental information disclosure and information sharing, and give play to the role of risk dispersion of green finance.

(2) Carry out the regional development strategy and implement differentiated green financial policies. In view of the differences in economic development level, industrial structure, resource endowment and other factors among provinces in China, governments at all levels should implement regional development strategies and implement differentiated green financial policies and environmental regulatory measures according to the actual regional development. As far as the eastern region is concerned, while strengthening financial support for the green environmental protection industry, it should also expand the cross-regional green financial reform and innovation pilot, realize the cross-regional flow of green financial resources, and give full play to the radiation-driven role of the pilot areas. For the central and western regions, we should pay more attention to the formation of the concept of green finance, expand the coverage of green finance business, strengthen its integration with traditional industries such as agriculture, tourism and energy, and give full play to the carbon emission reduction effect of green finance. The central people's government should also give full play to the role of macro-allocation, rationally distribute and dynamically allocate resources according to the actual situation of the region, and ensure the steady development of green economy in various regions on the basis of maximizing the efficiency of capital utilization. At the same time, the government can promote the green financial reform and innovation policy to all parts of the country, thus promoting the construction of a green financial system. In addition, commercial banks are encouraged to increase the scale of green credit, increase the investment in credit funds for green and clean industries (environmental protection, new energy and new materials), and at the same time reduce the funds flowing to the "two high" industries and strengthen the supervision of the use of funds.

(3) Innovate green financial products and services to improve the supply efficiency of green finance. Diversified green financial instruments provide investors with more choices to participate in financial transactions, improve market liquidity and reduce environmental risks. Guide financial institutions to support the green transformation and upgrading of small and micro enterprises, appropriately lower the financing threshold, innovatively launch diversified green credit products such as "chain loan", "green leaf loan", "e-commerce loan" and "family farm loan", broaden the financing channels for green enterprises and marginalized people, and effectively revitalize "carbon assets". At the same time, promote the application of green credit points and establish personal carbon accounts to stimulate green consumption, change the endogenous motivation of poverty alleviation, and achieve the dual goals of poverty reduction and ecological civilization. In addition, financial institutions should focus on strengthening financing support for new energy, low-carbon environmental protection and other strategic emerging industries, and promote technological transformation of enterprises and industrial optimization and upgrading, so as to shorten the effective time of carbon emission reduction effect and weaken the lag effect of green finance carbon emission reduction effect.

(4) Strengthen the synergistic effect of environmental regulation and green finance, and continuously improve the optimal combination and innovation of various environmental regulation tools. Any environmental regulatory tool has its own advantages and limitations. There is no optimal regulatory policy that can reduce carbon emissions and achieve green industrial development. It is necessary to adopt a comprehensive regulatory tool that integrates standards and regulatory policies, fiscal and taxation policies, voluntary agreements, information tools and technology research and development policies. According to the actual situation in different regions, the government can introduce detailed preventive measures, improve the level of law enforcement team, and avoid inefficient environmental protection behaviors that interfere with the normal operation and production of enterprises and inhibit their enthusiasm for production on the grounds of strengthening pollution control. At the same time, we should safeguard the right of independent production and management of enterprises, strive to create a fair competitive market environment, optimize the business environment, and encourage enterprises to change their environmental governance from "end governance" to "front prevention" to minimize the efficiency loss of administrative environmental governance.

6.3 Research limitation

Although this paper provides some enlightenment for the government's decision making and research in the field of carbon emission reduction and green finance, it still has some limitations. Firstly, due to the availability of data, this paper uses provincial data to discuss the impact of the development level of green finance on carbon emissions in China from 2004 to 2021. Future research can explore the impact of green financial development level on corporate carbon emissions by adjusting research methods and perspectives. Secondly, from the research area, as the vanguard of actively promoting the integration of green finance and green industry, the green finance reform and innovation experimental zone has played an important role in promoting the effective transformation of ecological resources. Therefore, in the future, the green financial reform and innovation pilot zone can be included in the research framework, so as to draw more profound conclusions. Finally, the global principal component analysis (GPCA) can be considered for the measurement of green financial index in future research. GPCA is an analysis of panel data, which can reflect the dynamic changes of research objects, and it is objectively weighted according to the correlation between indicators, thus enhancing the desirability of indicators' calculation results.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: The datasets used or analysed during the current

study are available from the corresponding author on reasonable request.

Author contributions

XG: Writing–original draft. JY: Writing–original draft, Writing–review and editing. YS: Writing–review and editing. XZ: Writing–review and editing.

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Conflict of interest

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The impact of ESG performance on firms' technological innovation: evidence from China

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Technological innovation is crucial for creating sustainable corporate value and shaping competitive advantage in the market. ESG, as an indicator of corporate value practices, plays a significant role in enterprise technological innovation. However, there is little empirical evidence to support this claim. This study analyzes the relationship between ESG performance and technological innovation in Chinese A-share listed enterprises from 2011 to 2021. The statistical data shows that strong ESG performance has a significant positive impact on corporate technological innovation. ESG performance can promote corporate technological innovation through external mechanisms, such as enhancing corporate network location and increasing institutional shareholding. Additionally, internal mechanisms, such as reducing labor costs and easing financing constraints, can also promote corporate technological innovation. The impact of ESG performance on corporations exhibits heterogeneity, with ESG performance promoting innovation more strongly among labor-intensive firms, non-state-owned firms, highly competitive industries, and mature firms. Based on the study results, it is recommended that enterprises actively practice ESG development concepts, optimize their equity structure, strengthen information communication with stakeholders, and alleviate problems such as information asymmetry to improve their technological innovation. The government should focus on enterprise characteristics, improve ESG development policies, and promote enterprise innovation through ESG performance.

KEYWORDS

ESG, firm network location, labor costs, firm technological innovation, institutional shareholding, financing constraints

1 Introduction

ESG is a crucial framework for evaluating and directing corporate sustainability. The concept was first introduced in the *Who Cares Wins repor*[1] by the United Nations Global Compact in 2004. The three letters E, S, and G represent Environment, Social, and Governance, respectively, and encompass information on the company's impact on the environment, responsibility to society, and corporate governance. The acronym ESG stands for Environment, Social, and Governance. It encompasses information on the company's

1 *Who Cares Wins report* issued by the United Nations Global Compact Organization: https://www.unepfi.org/fileadmin/events/2004/stocks/who_cares_wins_global_compact_2004.pdf

impact on the environment, its responsibility to society, and its corporate governance. ESG is an emerging method of evaluating the non-financial aspects of enterprises. Given global challenges such as slow economic recovery, frequent extreme weather, wealth inequality, and labour issues, the ESG concept has become the international community's general consensus. This concept promotes multiple values and emphasises the coordinated development of the economy, environment, and society. An increasing number of large and medium-sized enterprises are taking ESG factors into account when making strategic decisions, and many are now publishing ESG reports (Tsang et al., 2023). In China, the ESG concept has opened doors for rapid development opportunities. According to *the Analysis Report on Business Performance of Chinese Listed Companies in 2022*[2], over 1,700 listed firms have compiled and published ESG-related reports for 2022, accounting for 34% of the total, which is an increase of over 300 from 2021. The ESG concept is well suited to China's major initiatives, including promoting high-quality development, achieving carbon peaking and carbon neutrality targets, and promoting common prosperity. Hence, it complies with the development needs of the new era.

ESG, as an indicator of corporate value practices, significantly impacts corporate operations. Empirical evidence supports the important role played by ESG in enhancing corporate performance, managing financial risks, and achieving corporate value (Friede et al., 2015; Fatemi et al., 2018; Broadstock et al., 2021). Moreover, technological innovations are the driving force behind sustainable creation of corporate performance and critical to shaping competitive advantage in the market (Li et al., 2019; Li et al., 2021). Hence, what is the impact of ESG on the progress of technological innovation within corporations? The existing body of literature on ESG and corporate technological innovation primarily focuses on examining the influence of specific dimensions of ESG performance on corporate technological innovation. Initially, scholars have analyzed the influence of corporate environmental responsibility on corporate technological innovation. Corporate environmental responsibility (ER) can impact a company's value by influencing technological innovation (Li Z. et al., 2020). Environmental regulation holds a noteworthy position in shaping the realm of green innovation by exerting influence and mediating the impact of environmental regulations on the progress and acceptance of green technological innovations. It serves as a crucial determinant that strengthens the impact and efficacy of these regulations in propelling the advancement of sustainable technologies. (Chang, 2011; Wang et al., 2021). Corporate environmental responsibility positively affects innovation legitimacy and enables companies to undertake innovative activities that align with environmental requirements (Xu et al., 2022). Secondly, previous research has shown that social responsibility plays a crucial role in enhancing companies' technological innovation (Martinez-Conesa et al., 2017). Significant disparities exist in the impacts of corporate adoption of social responsibility strategies on technological innovation. Proactive social responsibility strategies serve to promote corporate technological innovation, whereas passive social responsibility hampers it (Bocquet et al., 2013). Paruzel et al. (2023) explain how social responsibility affects corporate technological innovation through financing constraints, information asymmetry, and employee innovation within the firm. Thirdly, some scholars have posited that ineffective corporate governance impedes innovative activity (Belloc, 2012), whereas enhanced corporate governance encourages firms to adopt technological innovations (Tylecote and Ramirez, 2006; Jia et al., 2019). The influence of corporate governance on innovation promotion differs depending on the specific stage in which the company is operating (Chiang et al., 2013). Additionally, a limited number of studies examine the effect of ESG performance as a whole on the technological innovation of firms. Several studies have examined the impact of ESG on firms' green innovation and have reached a consensus that ESG ratings exhibit a notable positive effect on both the quantity and quality of firms' green innovation (Tan and Zhu, 2022). Other studies have centered on the correlation between ESG and firms' technological innovation, highlighting that ESG disclosure supports technological innovation and evaluating the internal factors of ESG ratings that impact technological innovation in firms (Chen et al., 2023; Li et al., 2023).

The extant literature has primarily focused on examining the impact of ESG on corporate technological innovation through the lenses of environmental sustainability, social responsibility, and corporate governance. This body of work has established a robust foundation for further inquiry into the intricate relationships between ESG and technological innovation. Considering China's low-carbon development strategy and sustainable development, it is worth investigating if ESG genuinely encourages technological innovation in corporations. If there is an effect, what is the mechanism of ESG in promoting corporate technological innovation? Does this effect differ based on firm characteristics? Answering the aforementioned questions is crucial in improving the innovation capabilities of enterprises, encouraging innovation-driven development, and ultimately achieving sustainable economic and social development.

Drawing upon the aforementioned discourse, this study investigates the association between ESG performance and corporate technological innovation in Chinese A-share listed companies spanning from 2011 to 2021. Additionally, it examines the influence of ESG performance on corporate technological innovation from external and internal viewpoints. The findings of the study indicate that proficient ESG performance plays a crucial role in fostering substantial advancements in technological innovation. The ESG performance of enterprises can enhance technological innovation through both external and internal mechanisms. External mechanisms include enhancing the location of corporate networks and increasing the proportion of institutional shareholdings. Internal mechanisms include improving labor costs and easing financing constraints. Furthermore, there exists heterogeneity in the influence of corporate ESG performance. Exceptional ESG performance exerts a more pronounced impact on promoting corporate technological innovation within labor-intensive firms, non-state-owned firms, industries characterized by high competition, and enterprises in the mature growth stage. The potential marginal benefits of this study are to: (1) Unlike previous studies that have examined the impact of ESG on corporate technological innovation from a single perspective, this paper presents a comprehensive examination of the impact of overall

2 *Analysis of Business Performance of Listed Companies in China for 2022*: https://www.capco.org.cn/sjfb/dytj/202305/20230505/j_20230505160830000168327423094519l0.html

ESG performance on corporate technological innovation. It extends the literature on the economic consequences of ESG and the factors influencing corporate technological innovation. Furthermore, this paper offers theoretical insights on how ESG can better encourage corporate technological innovation. (2) Existing research on the mechanisms of ESG's influence on corporate technological innovation has primarily focused on internal factors such as corporate debt, financing, and managers' environmental awareness. In contrast, this paper broadens the scope of the mechanisms by considering both internal and external factors of enterprises. It explores the financing mechanism and labor costs from an internal perspective of the enterprise. Additionally, it examines the roles of the enterprise's network location and the proportion of institutional shareholding from an external perspective. This approach provides a novel perspective for studying the mechanisms and processes of ESG's impact on enterprise technological innovation. (3) This paper comprehensively accounts for the impact of enterprise characteristics heterogeneity, such as labor intensity, ownership structure, market competition level, and stage of enterprise development, on both ESG and enterprise technological innovation. This approach aims to enhance the understanding of ESG's innovation effect, to promote the development of ESG practices, and to provide empirical support for more targeted study conclusions.

The study is structured in the following manner: the study's design is clarified in Section 3 once the theoretical analysis and research hypotheses have been presented in Section 2. Section 4 provides a summary of the empirical findings and analysis, whereas Section 5 explores the investigation of heterogeneity. Finally, policy ideas are presented in Section 6 to conclude the study.

2 Theoretical analysis and research hypothesis

2.1 ESG performance and corporate technological innovation

According to resource dependence theory, firms must obtain the necessary resources from the environment to sustain their production and operations. The more resources a firm has, the more it can reduce uncertainty in its production and operations, improve its ability to cope with risk, and thus invest more resources in its technological innovation activities (Pfeffer and Salancik, 2003). Thus, sustainable access to key resources is central to the survival and growth of firms. Since resources do not flow completely freely between different sectors, it is necessary for firms to acquire resources through interaction with other members of society, thus creating resource dependence. According to stakeholder theory, stakeholders will participate in the development of the firm, help the firm to share business risks, help the firm with financing and provide financial support for the firm's technological innovation activities. The innovation performance of enterprises is influenced by stakeholders, and stakeholders with stronger innovation capabilities can improve the innovation performance of enterprises (Li and Zajac, 2018). Favourable ESG performance enhances the transparency of enterprise information, diminishes information asymmetry between the enterprise and stakeholders, facilitates stakeholder involvement in enterprise innovation decisions, and the stakeholders' keen focus on innovation significantly propels the enterprise's technological advancement (Flammer and Kacperczyk, 2016).

According to reputation theory, corporate reputation is an intangible asset accumulated in the process of production and operation of enterprises, and is a key resource for enterprises to obtain and maintain their own advantages. Good corporate reputation can help enterprises obtain resources and reduce business risks, and enterprises can invest more resources in innovation and technology development (Mai et al., 2021). Enterprises adhering to the ESG development concept and actively fulfilling social responsibility can win good corporate reputation for enterprises. According to the signaling theory, good ESG performance helps enterprises to establish a good corporate image and release positive signals to the society, which can obtain more social resources and ultimately promote innovation (Lee et al., 2022). Drawing upon the aforementioned analysis, this study formulates the subsequent hypothesis:

H1: Good ESG performance enhances firms' technological innovation.

2.2 External mechanisms of ESG performance affecting corporate technological innovation

2.2.1 Network location of firms

Due to the complexity and uncertainty of innovation activities, firms are unable to obtain all the information and knowledge needed for innovation from internal sources alone and are forced to realize innovation through wider external cooperation (Escribano et al., 2009). As a result, a network of firms' technological innovation cooperation is formed through the continuous exchange of information and resources between firms, with each firm in the network in a different position and with different resources under its control. Being at the center of the network helps firms to access the information and resources they need for their innovation activities, which in turn helps them to innovate.

The main variables that measure the location of a firm's network are centrality and structural holes. Analyzing business networks entails looking at and identifying networks made up of companies connected via alliances, partnerships, and cooperative efforts. In this study, the term of centrality refers to valuing a company's significance in the larger network and its ability to exert control over essential resources required for the network's operation. (Wasserman and Faust, 1994). The higher the centrality, the more the firm is at the core of the network, the more resources and information the firm has access to, and the stronger the firm's ability to learn, absorb and transform new information and knowledge, which is conducive to promoting technological innovation (Tsai, 2001). Secondly, firms with higher centrality possess a greater number of information channels and sources, enabling them to effectively mitigate information asymmetry between the firm and stakeholders through the comparison of diverse information. This conducive scenario further enhances the prospects of technological innovation within the firm. Finally, enterprises with high centrality can establish links with more enterprises, which is more helpful for enterprises to select appropriate partners and promote innovation through mutual

learning and cooperation (Larcker et al., 2013). Structural holes refer to voids in the network framework that arise between nodes possessing information and resources, yet lacking direct connections or interrupted relationships. These gaps serve as a vital determinant of a firm's network positioning. Firms located in structural holes are more conducive to technological innovation because they play a central role in information exchange and have the advantage of access to and control over information (Burt, 1997). First, firms occupying structural holes have non-redundant and heterogeneous linkages and access to differentiated information domains that can be filtered and integrated for innovation (Kwon et al., 2020). Additionally, firms occupying structural holes have a greater propensity to discern the qualifications of potential trading partners and collaborators, as well as swiftly grasp opportunities or threats. This ability aids in circumventing innovation failures and augmenting the likelihood of innovation success (Uzzi, 1997). Finally, maintaining ties with many firms is costly, and firms that eliminate redundant ties can devote their limited managerial effort to the most valuable ties, which is beneficial for the efficiency of collaborative innovation (Gnyawali and Madhavan, 2001; Soda et al., 2004).

Favorable ESG performance has the potential to enhance a company's network position. On one hand, it can boost the company's reputation, which, to some extent, signifies its standing and influence within the network. The higher the status and influence, the more important the company's position in the network. Alternatively, favorable ESG performance communicates to the market and stakeholders the company's dedication to the principles of sustainable development. This highlights the company's focus on environmental conservation, social accountability, and corporate governance, resulting in heightened societal recognition. The higher the social recognition, the more the company is at the core of the network, and the more power the company has to control resources in the network (Wang et al., 2014). Powell et al. (2005) and others found that core companies with obvious advantages control the corporate network, and their network control power is brought about by their network position. Therefore, good ESG performance can help improve the firm's position, influence and control over resources, i.e., increase the firm's network position.

2.2.2 Institutional shareholding

Institutional investors, with their expertise and information advantages, have gradually become a major investor in the capital market. Compared with individual investors, institutional investors have more initiative to participate in corporate governance and are more able to influence firms' technological innovation decisions and actions and reduce short-sighted behavior (Jiang and Yuan, 2018). Institutional investors are able to gather more information about the firm and increase the transparency of corporate information, thereby alleviating corporate financing constraints to some extent (Cornett et al., 2007). Simultaneously, institutional investors, in their capacity as shareholders, can furnish ample financial support for firms' decisions and endeavors related to technological innovation.

Good ESG performance helps increase institutional shareholdings. Companies with good ESG performance tend to be larger, faster growing and more profitable companies, which are more preferred by institutional investors (Lin et al., 2014); optimal ESG performance augments the transparency of corporate disclosures and diminishes information asymmetry with the market, making them more appealing to institutional investors (Leuz et al., 2009; Bushee et al., 2014; McCahery et al., 2016); ESG performance can have a significant impact on company performance, which is also reflected in the stock market, making it easier to attract institutional investors to hold company shares.

Drawing upon the analysis presented above, the subsequent hypothesis is formulated:

H2a: Favorable ESG performance has the potential to enhance firms' technological innovation by augmenting their network positioning.

H2b: Favorable ESG performance can stimulate firms' technological innovation by augmenting institutional shareholding.

2.3 Internal mechanisms of ESG performance affecting firms' technological innovation

2.3.1 Financial constraints

Due to the high investment, risk, and long return cycle associated with innovation activities, companies facing high financing constraints may experience greater financial pressure and reduce their innovation inputs, ultimately inhibiting their technological innovation. Good ESG performance can alleviate financing constraints and promote technological innovation. In the first instance, as a form of non-financial information that is disseminated to external entities, ESG has the potential to mitigate information disparities between firms and markets. This can subsequently contribute to a decrease in external financing costs and assuage financing constraints experienced by firms, ultimately exerting a favorable impact on technological innovation (Dhaliwal et al., 2012; Zhang and Lucey, 2022). Secondly, good ESG performance can demonstrate corporate social responsibility, enhance corporate reputation, and build a positive corporate image. This can help to secure financial support from stakeholders, alleviate financing constraints, and promote technological innovation within the enterprise. Consequently, strong ESG performance assists companies in alleviating their financing constraints and securing external financial backing, thereby exerting a positive influence on corporate technological innovation (Zeng, 2018).

2.3.2 Labor costs

Favorable ESG performance is likely to lead to an escalation in the labor costs incurred by a company. First, in the social responsibility aspect of ESG, human resource management and development and employee health and safety are important manifestations of corporate social responsibility. Second, in the corporate governance aspect of ESG, wages, dividends and benefits are important components of corporate governance performance. For companies, good ESG performance must be achieved by continuously improving employee benefits and promoting human resource development, which will inevitably lead to rising labor costs. Rising labor costs, in turn, generate factor substitution effects, human capital enhancement effects, and innovation compensation effects that encourage firms to innovate technologically (Acemoglu, 2010; Antonelli and Quatraro, 2014). First, when labor costs rise, firms will choose to use capital and technology instead of labor, generating a factor substitution effect that promotes firms' technological

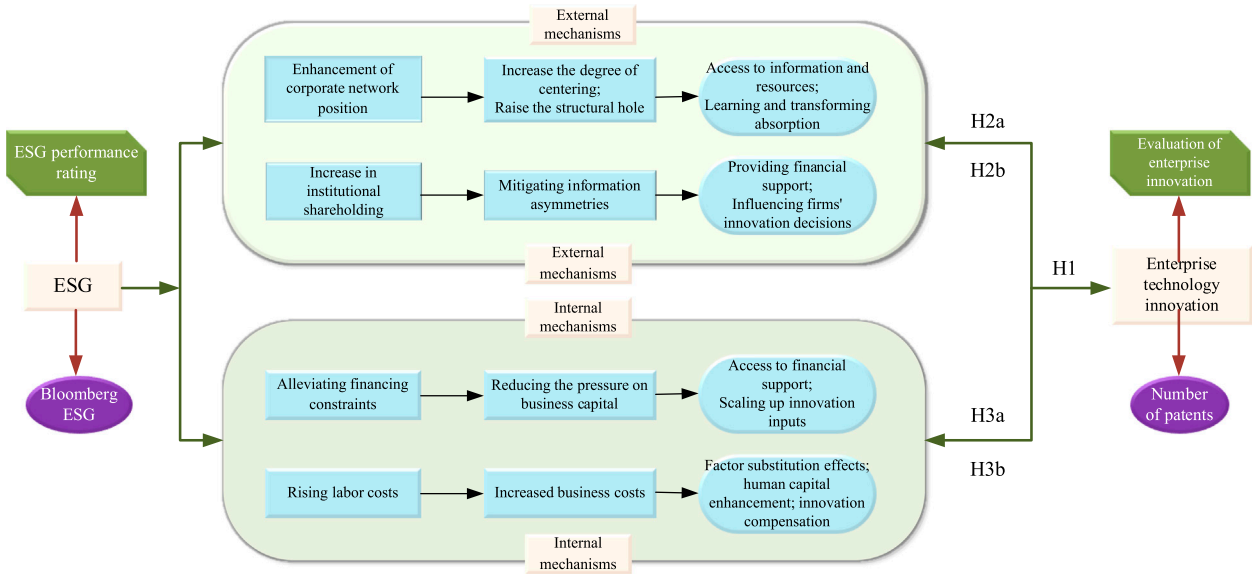


FIGURE 1
Mechanism of action of ESG performance on companies' technological innovation.

innovation. Second, rising labour costs lead to higher employee compensation. This in turn has a dual effect: it attracts more innovative employees to the firm and encourages the firm to improve talent training, thereby increasing the innovation efficiency of employees. (Hutchens, 1989). Finally, rising labor costs cause firms to increase production costs and reduce profits, which to some extent stimulates firms' demand for new technologies and compensates for lower profits caused by rising labor costs through technological innovation (Li J. et al., 2020). Therefore, good ESG performance leads to higher labor costs and thus promotes technological innovation in firms.

Drawing upon the analysis presented above, the subsequent hypothesis is formulated:

H3a: Good ESG performance can promote firms' technological innovation by alleviating financing constraints.

H3b: Good ESG performance leads to an increase in labor costs and thus promotes corporate technological innovation.

The specific mechanism of action is shown in Figure 1.

3 Research design

3.1 Model building

To examine the aforementioned research hypotheses, this study constructs a model to assess the influence of firms' ESG performance on their technological innovation:

$$Yit = \alpha 0 + \alpha 1 Esgit + \sum \alpha m Controlsit + \sum Industry + \sum Year + \varepsilon it \quad (1)$$

where i is firm and t is year. The explanatory variable Y denotes firms' technological innovation and, in the mechanism analysis, also firms' network location, institutional shareholding, financing constraints and labor costs. *ESG* is the core explanatory variable, firms' ESG rating scores. *Controls* denotes other possible control variables. In order to mitigate the influence of industry-specific factors that remain constant over time, the analysis incorporates industry-level fixed effects $\sum Industry$, and $\sum Year$ are time-fixed effects. The coefficient α_1 represents the estimated value of the main explanatory variable. A positive and statistically significant coefficient suggests that favorable ESG performance has a stimulating effect on firms' technological innovation.

3.2 Variable setting

3.2.1 Technological innovation of enterprises (*innovation*)

In line with the methodology adopted by Hsu et al. (2014), this study employs the count of patents granted to firms as a proxy for measuring the technological innovation output and evaluation of the level of innovation exhibited by enterprises. Because the number of patents granted is highly right-skewed, and if the number of patents granted is 0, it will cause missing values, so this study adopts the number of patents granted plus 1, and then takes the logarithm as the measure of enterprise technological innovation.

3.2.2 Enterprise ESG performance (*Esg*)

At present, scholars primarily rely on third-party rating agencies to assess the ESG performance of corporations. However, this study utilizes the Bloomberg ESG score as the primary explanatory variable to assess ESG performance in corporations. The Bloomberg ESG score comprises three crucial dimensions, namely, environmental, social, and corporate governance indicators, making it a comprehensive measure. A higher score denotes better fulfillment of relevant responsibilities by the

company. This indicator provides a comprehensive and objective reflection of a company's fulfillment of its environmental, social and corporate governance responsibilities.

3.2.3 Enterprise network location (*Centrality, SH*)

Enterprise network location is measured by degree centrality and structural holes (*SH*), the measure of centrality is degree centrality (*Centrality*), this study draws on the research of Freeman (1978), Burt (1992), degree centrality and structural holes of the calculation formula is as follows:

$$Centrality_i = \frac{1}{n-1}\sum_{i\neq j}\theta_{ij} \tag{2}$$

where θ_{ij} denotes whether or not there is a chain director relationship between node firms i and j. If there is a chain director relationship, it is assigned a value of 1, and if there is no chain director relationship, it is assigned a value of 0. n denotes the number of firms in the chain director network.

$$SHi = 1 - \sum_{j}\left(P_{ij} + \sum_{q}P_{iq}P_{qj}\right)^2 \tag{3}$$

where $q \neq i, j$; P_{ij} is the strength of the direct relationship from firm i to firm j; $P_{iq}P_{qj}$ denotes the strength of the indirect relationship from firm i to firm j through firm q; and $\sum_{q} P_{iq}P_{qj}$ denotes the sum of all the indirect relationships between firm i and firm j. The larger the difference, the richer the structural hole.

3.2.4 Institutional shareholding ratio (*INST*)

Following Fang and Na (2020) and Li and Lu (2015), this study uses institutional investors' holdings in listed firms to denote institutional shareholding.

3.2.5 Financing constraints (*Fc*)

Following Hadlock and Pierce (2010), this study constructs and measures the SA index using firm age (*Age*) and firm size (*Size*). Financing variables with endogenous characteristics are excluded to avoid endogenous interference and to better measure the degree of financing constraints of firms. Based on the study of Longsheng and Hui (2022), this study uses the logarithm of the absolute value of the SA index (*Fc*) to measure firms' financing constraints. The formula for calculating the SA index is as follows Hadlock and Pierce (2010):

$$SA = -0.737 \times Size + 0.043 \times Size^2 - 0.04 \times Age \tag{4}$$

3.2.6 Labor costs (*Wage*)

Labor cost refers to the expenses paid by enterprises (or all other types of units and institutions) for employing social labor, and its statistical accounting scope is theoretically larger than wages. As the definition and statistical scope of other forms of labor cost are not clear, this study makes reference to the investigation conducted by Xia and Dong (2014) and employs the average remuneration of employees as a metric to gauge labor costs.

3.2.7 Control variables

Size: The nature of R&D necessitates substantial, long-term investments. Large enterprises, with their inherent scale advantages, tend to enjoy more stable cash flows and possess greater access to financing options. Consequently, they are better equipped to allocate resources towards innovative projects. For the purpose of this study, we adopt the natural logarithm of total assets as a metric to capture the essence of size.

Age: Mature enterprises often accumulate rich experiences in innovation, leading to reduced costs and a more proactive approach towards R&D. Conversely, some argue that as companies age, they may become complacent about past successes and lose sight of the importance of ongoing innovation. Therefore, controlling for the age of the enterprise is crucial. For our analysis, we consider the number of years since the company's establishment as a metric of age.

Growth: Growth represents a company's potential for future expansion and its ability to identify and capitalize on investment opportunities. From a value perspective, growth signifies a company's capacity to generate outsized returns and its potential worth as a going concern. In this study, we employ sales revenue growth rate as a proxy for growth.

Financial Leverage (Lve): The equipment, personnel, and results of R&D activities possess unique characteristics that render their conversion costs substantial. Given the substantial nature of R&D investments and the associated risks, creditors often impose stringent conditions on the funding they provide to protect their interests. Consequently, lower financial leverage is more favorable for technological innovation investment. High levels of debt can have a negative impact on innovation investment decisions. For this study, we use total liabilities/total assets as a proxy for financial leverage.

Cash Flow (CF): Sustaining R&D activities requires significant cash flow investments. Firms without sufficient cash flow may struggle to maintain their R&D efforts. Therefore, adequate net cash flow is a crucial factor for firms to engage in R&D activities. We measure cash flow using the natural logarithm of net cash flow from operating activities.

Fixed Asset Share (Fasset): A higher fixed asset ratio indicates less liquid assets and potentially lower investments in innovation. This, in turn, may limit funds available for innovative R&D activities. To capture this aspect, we use net fixed assets/total assets as a metric for the fixed asset share.

Shareholding Concentration (Top1): A higher shareholding concentration ratio signifies that the primary shareholder holds a disproportionately large stake in the enterprise. This concentration of power not only enhances their voice in management and operational decisions but also grants them a greater say in strategic choices. In their pursuit of maximizing their own interests, these shareholders may be inclined to avoid high-risk, high-reward endeavors like innovation and research and development due to their long investment cycles and inherent uncertainties. Such a mindset often leads to more conservative investment strategies. This study employs the proportion of shares held by the largest shareholder as a metric to assess shareholding concentration.

Return on Total Assets (Roa): Return on Assets (ROA) serves as a proxy for the profitability of an enterprise. A higher ROA indicates that the enterprise is generating sufficient profits, thereby providing low-cost internal financing for innovative activities. This, in turn, not only supports the company's internal financing needs but also

sends positive signals to external financiers, making it easier for the enterprise to secure external financing for its innovative pursuits. In this study, we use net profit/total assets as a measure of Return on Total Assets.

3.3 Sample selection and data source

In order to ensure the availability and consistency of the research data, this study takes the Shanghai and Shenzhen A-share listed companies in 2011–2021 as the research object, and processes the samples as follows: (1) exclude the companies belonging to ST, *ST and PT during the sample period; (2) exclude the financial companies; (3) exclude the samples with missing data; and finally obtain 5,091 company annual observation data.

This study draws upon data from two primary sources: firm innovation data sourced from the CNRDS database and ESG data obtained from the Bloomberg database[3]. The network location of firms is obtained based on board members who are also directors of different firms, forming a chain director network of firms. To obtain the location data for the chain director network, this study downloaded information on board members of the sample firms from the CSMAR database from 2011 to 2021. Concurrent positions of directors between different firms were identified based on information such as directors' names, gender, and age. If any two firms had at least one common director in year t, then a chain director relationship was established. After identifying the director relationships between firms in the chain, the next step is to calculate the network centrality and structural holes for each firm. These calculations are performed utilizing the Python programming language, which provides a robust and versatile platform for performing such analyses. Institutional Shareholding Ratio (*INST*), financing constraint (*Fc*), labor cost (*Wage*), firm industry size (*Size*), firm age (*Age*), firm growth (*Growth*), financial leverage (*Lve*), firm cash flow (*CF*), fixed asset share (*Fasset*), equity concentration (*Top1*) and return on total assets (*Roa*). The financial data utilized in this research are sourced from the CSMAR database. In order to mitigate the impact of extreme outliers, all continuous variables in this study have undergone Winsorization at the upper and lower 1% thresholds.

3.4 Analysis of descriptive statistics

Table 1 displays the descriptive statistics of the variables, with the mean value of firms' technological innovation level (*Innovation*) estimated as 1.990. The level of technological innovation among the analyzed enterprises is measured on a numerical scale, with the highest recorded value being 9.588. This indicates the greatest degree of technological innovation achieved. Conversely, the minimum recorded value is 0, indicating a lack or absence of technological innovation in certain companies. Additionally, the standard deviation is estimated at 1.979, signifying that there exists substantial variability in the level of innovation across different firms. The maximum value of ESG performance (*Esg*) is 68.917, the minimum value is 6.198, and the standard deviation is 9.713, which indicates that there are different ESG performances in different enterprises.

4 Empirical results and analysis

4.1 Benchmark regression analysis

Table 2 presents the outcomes of the benchmark regression analysis conducted in this study. In column (1), the regression analysis reveals a statistically significant positive coefficient of ESG performance (*Esg*) on firm technological innovation (*Innovation*), indicating that firms with a competitive edge in ESG factors exhibit higher levels of technological innovation, even without the inclusion of control variables and time-industry fixed effects. As shown in columns (2)–(3), the regression coefficient of the variable *Esg* is still significantly positive at the 1% level when only industry fixed effects or time fixed effects are added after adding control variables. Based on the results outlined in column (4) of the analysis, it is apparent that the regression coefficient indicating the correlation between ESG performance and corporate technological innovation (*Innovation*) is estimated to be 0.027, which is still significant at the 1% level when controlling for both industry and time fixed effects. These results suggest that good ESG performance has a significant positive impact on firms' technological innovation. This is consistent with the conclusion of Li et al. (2023). Hence, hypothesis H1 is accepted.

4.2 Robustness test

4.2.1 Transformation of the regression model

In the benchmark regression, this study adopts the panel fixed effects model for regression. The chosen explanatory variable in this study is the number of patents granted. Due to the nature of patenting processes, it is possible to observe a significant number of zero values. To address this issue, we employ the Tobit model as an appropriate statistical framework. This study adopts the Tobit model to test whether the regression results of the above fixed effects model are robust. The results from analyzing column (1) of Table 3 show that a positive correlation between sound ESG performance and firms' technological innovation still exists and is statistically significant. This indicates that the key findings and conclusions derived from this study are durable and dependable, offering convincing proof to affirm that effective ESG performance can propel technological innovation within companies.

4.2.2 Transformation of the explanatory variables

By utilizing the total count of patents granted by firms to measure technological innovation, this study aims to capture the breadth and diversity of technological advancements achieved by different firms in the regression. Patents can be categorized into three types: invention patents, utility model patents, and design patents. Among these, invention patents serve as a measure of the innovation quality of enterprises, providing a more comprehensive reflection of their substantive technological innovation.

3 The Bloomberg database: ESG Bloomberg Professional Services: https://www.bloomberg.com/professional/solution/bloomberg-terminal/

TABLE 1 Descriptive statistics of the main variables.

Variable	Symbol	N	Mean	Std	Minimum	Maximum
Enterprise technology innovation	*Innovation*	5,091	1.990	1.979	0.000	9.588
ESG performance	*Esg*	5,091	28.915	9.713	6.198	68.917
Centrality	*Centrality*	5,091	0.004	0.003	0.002	0.025
Structure hole	*SH*	5,091	0.256	0.279	−0.125	0.850
Institutional shareholding ratio	*INST*	5,091	0.605	0.222	0.000	1.557
Finance constraints	*Fc*	5,091	3.751	0.306	2.109	4.713
Labor cost	*Wage*	5,091	11.749	0.572	8.699	16.000
Enterprise scale	*Size*	5,091	23.472	1.393	19.847	28.636
Enterprise age	*Age*	5,091	18.167	5.916	3.000	42.000
Enterprise growth	*Growth*	5,091	0.373	4.977	−0.876	251.211
Financial leverage	*Lve*	5,091	0.477	0.189	0.014	1.056
Cash flow	*CF*	5,091	20.611	1.645	10.753	26.628
Fixed assets share	*Fasset*	5,091	0.245	0.187	0.000	0.954
Shareholding concentration	*Top1*	5,091	0.390	0.164	0.036	0.877
Return on total assets	*Roa*	5,091	0.056	0.058	−0.691	0.517

SH, The existence of no direct connection or intermittent relationship between certain in the network, the more structural holes associated with a node, the more important the node; INST, the proportion of company shares held by institutional investors; Fc, the absolute value of the SA index used, the higher the value, the greater the degree of financing constraints; Wage, the labour cost of the firm measured using average compensation; Size, Measures the size of the firm using the total assets of the firm; Age, Indicates the year the firm was founded; Growth, The growth rate of the company's sales revenue, indicating the potential future growth of the company; Lve, indicates the company's gearing ratio; CF, indicates the natural logarithm of the firm's net cash flow; Fasset, Indicates the share of fixed assets in total assets; Top1, the shareholding of the first largest shareholder; Roa, we use net profit/total assets as a measure of Return on Total Assets.

Consequently, this study utilizes the count of invention patents granted by enterprises, rather than the overall count of patents, as the explanatory variable to assess the resilience of the aforementioned regression findings. Building on the studies by Tan et al. (2014) and Tong et al. (2014), this study utilizes a natural logarithmic transformation of the total number of patents awarded to companies, with the addition of 1. The findings presented in column (2) of Table 3 demonstrate that positive ESG performance continues to play a vital role in driving firms' technological innovation, which reinforces the robustness of the central conclusions drawn in this study.

4.2.3 Transformation of explanatory variables

In this study, the Huazheng ESG rating (*Hzesg*) for the sample companies is employed as an alternative core explanatory variable in robustness testing, replacing the Bloomberg ESG rating. Here, Huazheng ratings are assigned values: 9 levels from C to AAA are assigned values from 1 to 9. The results of the regression analysis, as reported in column (3) of Table 3, demonstrate that the positive relationship between good ESG performance and companies' technological innovation remains statistically significant. These findings provide convincing evidence in support of the primary conclusions of the study, hence attesting to the robustness and dependability of the study's principal outcomes.

4.2.4 Change in sample interval

Due to the severe impact of the new crown epidemic in 2020 and 2021, the production and business environment of firms may have changed dramatically, and ignoring this factor may affect the robustness of the regression results. In this study, based on the study of Cao et al. (2023), we exclude the impact of the epidemic factor, limit the sample interval to 2011–2019, and re-run the regression, and the results are shown in column (4) of Table 3, which shows that the role of good ESG performance in promoting technological innovation of enterprises is still significant, suggesting that the core conclusions of this study are robust.

4.2.5 Excluding the four first-tier cities

Since the economic development level of the four first-tier cities (Beijing, Shanghai, Guangzhou, and Shenzhen) is significantly different from that of other cities, and the economic development level of the region where firms are located significantly influences their business environment, this study adopts the study by Yu et al. (2018) and re-runs the regression after removing the sample of enterprises in the four first-tier cities, and the results are shown in column (5) of Table 3. The results show that the role of good ESG performance in promoting technological innovation of enterprises remains significant, indicating that the core findings of this study are robust.

4.3 Endogeneity treatment

4.3.1 Omitted variables

To reduce the likelihood of omitted variables or unobservable effects in the model, this study implements the methods outlined in Tang et al. (2020), including controlling for "time-industry" joint

TABLE 2 Base regression results.

Variable	(1)	(2)	(3)	(4)
Esg	0.045***	0.027***	0.041***	0.027***
	(7.195)	(4.248)	(4.217)	(3.540)
Size		0.228***	0.172**	0.225***
		(3.315)	(2.119)	(3.276)
Age		−0.020**	−0.039***	−0.022**
		(-2.107)	(-3.135)	(-2.084)
Growth		−0.011***	−0.012***	−0.011***
		(-2.879)	(-5.788)	(-3.092)
Lve		−0.357	−0.280	−0.315
		(-1.030)	(-0.691)	(-0.889)
CF		0.076**	−0.009	0.077**
		(2.298)	(-0.227)	(2.285)
Fasset		−0.114	−0.062	−0.104
		(-0.318)	(-0.175)	(-0.286)
Top1		−0.366	−1.148***	−0.367
		(-1.179)	(-2.764)	(-1.180)
Roa		1.681**	3.076***	1.827**
		(2.352)	(3.557)	(2.510)
Constant	0.703***	−5.374***	−2.165	−5.518***
	(4.230)	(-3.722)	(-1.312)	(-3.774)
Year	No	No	Yes	yes
Industry	No	Yes	No	Yes
N	5,091	5,091	5,091	5,091
R^2	0.048	0.343	0.083	0.348

t-values, indicated within parentheses, represent the significance levels of *, **, and ***, denoting statistical significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors are employed with firm-level clustering to account for potential heterogeneity within firms.

fixed effects at a higher order, controlling for time-varying industry-level unobservable variables, and re-estimating the regressions. The regression results, as shown in column (1) of Table 4, provide further evidence supporting the enduring importance of favorable ESG performance in fostering technological innovation within firms. These findings reinforce the strength and validity of the fundamental conclusions drawn in this study.

4.3.2 Two-way causality

The regression outcomes from the benchmark analysis indicate a positive relationship between a company's ESG performance and its level of technological innovation. Specifically, as a company's ESG performance improves, there is a corresponding increase in its level of technological innovation. However, it is also possible that the issue of endogeneity resulting from bidirectional causality emerges due to the fact that firms exhibiting high levels of innovation tend to be more proactive in enhancing their ESG performance. In order to mitigate the two-way causality problem, this study draws on the study of Longsheng and Hui (2022) and selects the one-period lagged term (*L_Esg*) and the two-period lagged term (*L2_Esg*) of the explanatory variable (*Esg*) as the explanatory variables, and re-runs the regression. The regression results, as shown in columns (2)–(3) of Table 4, show that the coefficients of *L_Esg* and *L2_Esg* are still significantly positive, indicating that the key findings of the study remain robust.

4.3.3 Instrumental variables

This study employs the mean (*Esg_mean*) of the ESG performance of other listed companies within the province of the focal enterprise as an instrumental variable. The use of 2SLS for instrumental variable regression allows us to account for potential endogeneity issues in our analysis. Notably, the instrumental variable is chosen based on the premise that other listed companies in the same provincial location as our sample enterprises share a similar

TABLE 3 Robustness test.

Variable	(1)	(2)	(3)	(4)	(5)
	Innovation	Invention	Innovation	Innovation	Innovation
Esg	0.037***	0.026***		0.032***	0.032***
	(3.665)	(4.180)		(3.833)	(3.268)
Hzesg			0.143***		
			(4.109)		
Size	0.284***	0.249***	0.262***	0.247***	0.206***
	(2.924)	(4.328)	(3.902)	(3.544)	(2.642)
Age	−0.040***	−0.009	−0.023**	−0.022**	−0.038***
	(-2.598)	(-1.126)	(-2.173)	(-2.003)	(-3.061)
Growth	−0.027**	−0.007***	−0.010***	−0.011**	−0.011***
	(-2.290)	(-2.764)	(-2.894)	(-2.372)	(-3.395)
Lve	−0.418	−0.448	−0.338	−0.382	0.384
	(-0.835)	(-1.502)	(-0.940)	(-1.052)	(0.974)
CF	0.079	0.067**	0.089***	0.058*	0.055
	(1.620)	(2.349)	(2.635)	(1.693)	(1.425)
Fasset	−0.149	−0.192	−0.118	−0.119	−0.924**
	(-0.284)	(-0.670)	(-0.325)	(-0.333)	(-2.167)
Top1	−0.629	−0.444	−0.387	−0.337	−0.182
	(-1.432)	(-1.644)	(-1.228)	(-1.093)	(-0.524)
Roa	2.472**	−0.151	1.840**	2.029***	1.803**
	(2.302)	(-0.267)	(2.525)	(2.650)	(2.305)
Constant	−7.580***	−6.418***	−7.028***	−5.912***	−4.770***
	(-3.894)	(-5.110)	(-4.879)	(-3.936)	(-2.961)
Year	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes	Yes
N	5,091	5,091	5,079	4,135	3,359
R^2		0.307	0.346	0.356	0.345

t-values, indicated within parentheses, represent the significance levels of *, **, and ***, denoting statistical significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors are employed with firm-level clustering to account for potential heterogeneity within firms.

institutional environment. This correlation between instrumental variables and the institutional environment within the same province ensures that the chosen instrumental variable is exogenous to the technological innovation of our sample firms. Crucially, the ESG performance of these other firms within the same province is assumed to have no direct impact on the technological innovation of our sample firms, further reinforcing the exogenous nature of our instrumental variable. To address this relationship, the instrumental variable approach is employed to address potential endogeneity issues and establish a causal relationship between a firm's ESG performance and its financial performance in this study. The two-stage least squares (2SLS) approach is employed to conduct instrumental variable regression. Table 4, column (4) presents the results of the first stage regression, the coefficient of the instrumental variable (*Esg_mean*) is significantly positive at 1% level, indicating that the selected instrumental variable is highly positively correlated with ESG performance. Column (5) presents the results of the second stage regression based on Cragg-Donald Wald F = 335.335, {S-Y10% critical value: 16.38}; Kleibergen-Paap rk LM = 78.578, *p*-value less than 0.001 and Kleibergen-Paap rk Wald F = 117.543, {The results of statistics such as S-Y10% critical value: 16.38} indicate that the weak instrumental variables test is passed and there is no over-identification. In the second stage, the coefficient of ESG performance is significantly positive at the 1% level, suggesting that despite addressing endogeneity concerns, positive ESG performance remains a driving factor of firms' technological innovation. Furthermore, the key findings of the study remain robust.

TABLE 4 Endogenous treatments.

Variable	Interaction fixed effect	Lagged explanatory variables		Instrumental variable test	
				Phase 1	Phase 2
	(1)	(2)	(3)	(4)	(5)
	Innovation	Innovation	Innovation	pbesg	Innovation
Esg	0.027***				0.081***
	(3.450)				(2.921)
L_Esg		0.028***			
		(3.026)			
L2_Esg			0.029**		
			(2.542)		
Esg_mean				0.754***	
				(10.842)	
Size	0.233***	0.234***	0.306***	2.394***	0.083
	(3.281)	(2.714)	(3.054)	(11.104)	(0.869)
Age	−0.022**	−0.018	−0.019	0.066*	−0.026**
	(-2.018)	(-1.411)	(-1.250)	(1.855)	(-2.408)
Growth	−0.011***	−0.043**	−0.200***	−0.005	−0.010***
	(-2.652)	(-2.354)	(-4.012)	(-0.338)	(-3.107)
Lve	−0.319	−0.535	−0.550	−2.456**	−0.134
	(-0.878)	(-1.176)	(-1.069)	(-2.031)	(-0.376)
CF	0.076**	0.113**	0.061	0.451***	0.051
	(2.155)	(2.252)	(0.983)	(3.987)	(1.438)
Fasset	−0.138	−0.276	−0.077	−1.055	−0.015
	(-0.368)	(-0.627)	(-0.159)	(-0.795)	(-0.040)
Top1	−0.358	−0.530	−0.510	−1.796*	−0.327
	(-1.121)	(-1.404)	(-1.178)	(-1.650)	(-1.059)
Roa	2.044***	1.729*	2.285**	0.995	1.897***
	(2.678)	(1.715)	(1.978)	(0.438)	(2.588)
Constant	−6.094***	−6.115***	−6.855***	−56.817***	−2.948
	(-4.043)	(-3.385)	(-3.340)	(-12.601)	(-1.586)
Cragg-Donald Wald F					335.335
					{16.38}
Kleibergen-Paap rk Wald F					117.543
					{16.38}
Kleibergen-Paap rk LM					78.578
					[0.000]
Year	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes	Yes
N	5,091	3,221	2,471	5,091	5,091

(Continued on following page)

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TABLE 4 (*Continued*) Endogenous treatments.

Variable	Interaction fixed effect	Lagged explanatory variables		Instrumental variable test	
				Phase 1	Phase 2
	(1)	(2)	(3)	(4)	(5)
	Innovation	Innovation	Innovation	pbesg	Innovation
R^2	0.359	0.371	0.380	0.612	0.319

t-values in parentheses, *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors are treated with firm-level clustering. The *p*-value of the statistic is in [] and the critical value at the 10% level of the Stock-Yogo test is in {}.

TABLE 5 Mechanism of action tests.

Variable	Enterprise network locations		Institutional shareholding	Financing constraints	Labor costs
	(1)	(2)	(3)	(4)	(5)
	Centrality	*SH*	*INST*	*Fc*	*Wage*
Esg	0.0000223**	0.002***	0.003***	−0.003***	0.004**
	(2.566)	(2.848)	(4.761)	(-5.643)	(2.301)
Size	0.0001976***	0.033***	0.031***	−0.128***	0.057***
	(2.618)	(4.835)	(5.700)	(-17.408)	(3.433)
Age	0.0000107	0.001	0.003***	0.042***	−0.000
	(0.928)	(1.165)	(2.616)	(66.081)	(-0.159)
Growth	0.0000121***	0.001***	0.000	0.000*	−0.001
	(3.494)	(4.144)	(0.896)	(1.725)	(-0.937)
Lve	0.0001318	−0.009	0.055*	0.134***	−0.108
	(0.339)	(-0.238)	(1.815)	(4.410)	(-1.162)
CF	0.000082*	0.002	0.007**	−0.003	0.023**
	(1.816)	(0.398)	(2.033)	(-1.147)	(2.364)
Fasset	0.0000775	0.016	−0.017	−0.017	−0.296***
	(0.192)	(0.451)	(-0.592)	(-0.772)	(-2.933)
Top1	0.0004081	0.021	0.635***	−0.011	0.217**
	(1.048)	(0.601)	(20.794)	(-0.452)	(2.481)
Roa	−0.0006928	−0.086	0.328***	0.104*	0.222
	(-0.648)	(-0.909)	(4.025)	(1.816)	(0.978)
Constant	−0.009672	−0.612***	−0.593***	6.006***	9.183***
	(-0.676)	(-5.106)	(-5.871)	(37.691)	(28.471)
Year	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes	Yes
N	5,091	5,091	5,091	5,091	5,091
R^2	0.153	0.104	0.444	0.867	0.351

t-values in parentheses, *, **, and *** denote significance at the 10 per cent, 5 per cent, and 1 per cent levels, respectively. Robust standard errors are treated with firm-level clustering.

4.4 Mechanism test

4.4.1 External mechanism test

There are a large number of studies confirming the positive impact of corporate network location on firm technological innovation (Ahuja, 2000; Woods et al., 2019). To test whether corporate network location is one of the mechanisms through which ESG promotes corporate technological innovation, this study takes corporate network location (*Centrality*, *SH*) as an explanatory variable and conducts regression analyses on ESG performance (*Esg*) and corporate network location, and the outcomes are presented in columns (1)–(2) of Table 5, where the regression coefficients for the relationship between ESG advantage (*Esg*) and *Centrality*, as well as *SH*, are observed to be significantly positive at a significance level of 1%. This suggests a substantial enhancement in corporate technological innovation resulting from the ESG advantage. Similarly, the coefficients for the firm's network position are also significantly positive, implying that ESG advantage enhances the firm's central position and control in the network, thus promoting technological innovation. Hence, hypothesis H2a is accepted.

A large number of studies have confirmed the positive impact of institutional shareholding on firms' technological innovation (Manso, 2011; Aghion et al., 2013). To verify that institutional shareholding is one of the mechanisms through which ESG promotes firms' technological innovation, this study takes institutional shareholding (*INST*) as an explanatory variable and conducts regression analyses on ESG performance (*Esg*) and institutional shareholding, and the results are shown in column (3) of Table 5. The coefficient of Esg is significantly positive, suggesting that ESG performance can effectively increase firms' institutional shareholding and thus promote firms' technological innovation. This is consistent with the findings of Bai et al. (2022). Hence, hypothesis H2b is accepted.

4.4.2 Internal mechanisms

A large number of studies have been conducted to confirm the negative impact of financing constraints on firms' R&D (Brown et al., 2009; Mancusi and Vezzulli, 2010). To examine the role of financing constraints as a mediating factor in the relationship between ESG performance and firms' technological innovation, this study employs financing constraints as an independent variable and performs regression analyses on both ESG performance (*Esg*) and financing constraints (*Fc*). The findings, presented in column (4) of Table 5, provide evidence supporting the presence of such a mechanism. The estimated coefficient of *Esg* is significantly negative, indicating that ESG advantage obviously alleviates the problem of firms' financing constraints and further promotes their technological innovation development. This is consistent with the findings of He et al. (2023). Hence, hypothesis H3a is accepted.

The research validates the positive influence of labor costs on firms' technological innovation (Acemoglu, 2010; Wei et al., 2020). To verify that financing constraints is one of the mechanisms through which ESG promotes firms' technological innovation, this study takes labor cost (*Wage*) as an explanatory variable and conducts a regression analysis between ESG performance (*Esg*) and labor cost, and the outcomes are presented in column (5) of Table 5, where a statistically significant positive regression coefficient for the relationship between labor cost and *Esg* on Wage is observed at a significance level of 5%. This implies that firms' labor costs play a significant role as a mechanism through which ESG performance influences an important aspect of firms' technological innovation. Hence, hypothesis H3b is accepted.

5 Heterogeneity analysis

5.1 Labor intensity

Labor intensity can affect the relationship between ESG performance and firms' technological innovation. From one perspective, labor-intensive companies typically allocate a higher proportion of their production costs to labor expenses. As labor costs rise, firms will gradually choose capital and technology to replace labor, creating a factor substitution effect that promotes firms' technological innovation. Second, labour-intensive enterprises typically possess more human capital. Improving this capital can attract innovative workers to join the enterprise and encourage the enterprise to strengthen talent training, thereby improving the innovation efficiency of employees. Therefore, this study argues that the role of ESG performance in promoting enterprise technological innovation is more significant in labor-intensive enterprises. To test the above inference, this study draws on the studies of Huang et al. (2023) and Zhao and Li (2016), and compares the amount of capital *per capita* of enterprises with their median, divides labor-intensive enterprises and non-labor-intensive enterprises, and conducts a subsample regression. In this case, the formula for capital per employee is (firm size)/total assets/number of employees. The regression results are shown in columns (1) and (2) of Table 6, where the regression coefficients of ESG performance on firms' technological innovation are more significant in labor-intensive firms, suggesting that good ESG performance stimulates technological innovation more effectively in labor-intensive firms.

5.2 Type of ownership

The connection between ESG performance and firms' technological innovation might exhibit variations based on the ownership structure of the firm. In comparison to state-owned enterprises (SOEs), non-state-owned enterprises (non-SOEs) potentially encounter more pronounced financial constraints and have a greater urgency for research and development (R&D) funding. ESG may help non-SOEs to reduce the pressure on funds used for R&D, give them incentives to increase R&D investment, and enhance the firm's innovation capability. In addition, compared to SOEs, non-SOEs may be at the edge of the corporate network, and good ESG performance can improve the corporate network position of non-SOEs, which is conducive to non-SOEs' technological innovation. Based on the analysis and theory presented in this study, it is posited that ESG performance has a greater impact on enhancing technological innovation in non-state-owned enterprises. To validate the aforementioned assertion, this study distinguishes the sample enterprises into two categories: state-owned enterprises (SOEs) and non-state-owned enterprises (non-SOEs). Group regression is then performed, and the outcomes are presented in columns (3) and

TABLE 6 Heterogeneity analysis.

Variables	Labor-intensive	Non-labor intensive	State enterprise	Non-state enterprise	Highly competitive industries	Low-competition industries	Growth period	Maturity period
	(1)	(2)	(3)	(4)	(5)	(6)	(6)	(8)
Esg	0.031***	0.017*	0.021**	0.034***	0.033***	0.023**	0.031	0.026***
	(2.952)	(1.719)	(2.070)	(3.195)	(3.766)	(2.133)	(1.409)	(3.426)
Size	0.176*	0.353***	0.346***	0.114	0.259***	0.216**	−0.145	0.273***
	(1.716)	(3.951)	(3.834)	(1.246)	(2.966)	(2.371)	(-0.858)	(3.927)
Age	−0.022	−0.022	0.014	−0.047***	−0.017	−0.022*	0.015	−0.031***
	(-1.639)	(-1.545)	(0.883)	(-3.841)	(-1.141)	(-1.664)	(0.271)	(-2.663)
Growth	−0.045***	−0.007***	−0.054***	−0.011***	−0.016***	−0.010***	−0.409**	−0.011***
	(-2.815)	(-3.207)	(-2.739)	(-3.514)	(-2.810)	(-2.930)	(-2.328)	(-3.327)
Lve	0.416	−0.971**	−0.856*	0.546	−1.407***	0.673	1.363	−0.447
	(0.943)	(-2.104)	(-1.687)	(1.229)	(-2.926)	(1.551)	(1.599)	(-1.212)
CF	0.072	0.067	0.038	0.123***	0.044	0.118**	−0.015	0.089***
	(1.531)	(1.565)	(0.804)	(2.808)	(0.991)	(2.562)	(-0.146)	(2.607)
Fasset	−0.592	0.086	0.165	−0.700	0.436	−0.447	−1.266	−0.146
	(-1.131)	(0.196)	(0.365)	(-1.275)	(0.883)	(-0.984)	(-1.127)	(-0.396)
Top1	−0.527	−0.339	−0.158	−0.279	0.403	−0.853**	−1.302*	−0.237
	(-1.326)	(-0.770)	(-0.322)	(-0.737)	(0.973)	(-2.166)	(-1.793)	(-0.737)
Roa	2.586***	0.857	2.258*	1.377*	0.173	3.561***	6.753***	1.515**
	(2.841)	(0.755)	(1.699)	(1.744)	(0.195)	(3.640)	(2.629)	(2.084)
Constant	−4.325**	−7.994***	−8.127***	−3.766**	−5.764***	−5.594***	4.417	−6.696***
	(-2.042)	(-4.440)	(-4.246)	(-2.075)	(-3.071)	(-3.124)	(1.367)	(-4.534)
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	2,542	2,549	2,780	2,311	2,491	2,600	474	4,617
R^2	0.349	0.368	0.380	0.362	0.343	0.382	0.340	0.364

t-values in parentheses, *, **, and *** denote significant at the 10%, 5%, and 1% levels, respectively. Robust standard errors are treated with firm-level clustering.

(4) of Table 6. The results reveal that the regression coefficients of ESG on enterprise technological innovation are larger in the sample of non-SOEs, indicating that favorable ESG performance holds greater efficacy in fostering the innovative progression of non-SOEs.

5.3 Degree of industry competition

The potential influence of ESG performance on companies' technological innovation could be contingent upon the degree of competition within their respective industries. In competitive industries, firms must continuously improve their competitive advantages. Good ESG performance can help build a corporate image, enhance corporate reputation, and improve firms' technological innovation. This is crucial for enhancing firms' competitiveness. Accordingly, this study hypothesizes that the more competitive the industry, the stronger the role of ESG performance in promoting technological innovation. To examine the aforementioned hypothesizes, this study relies on the research conducted by Peng et al. (2018) as the foundation for measuring the level of industry competition through calculating the Herfindahl index. By utilizing the median value of the Herfindahl index as the benchmark for categorization, the industries in which the sample companies operate are divided into high-competition and low-competition sectors. Building upon the diligent analysis and theoretical structure presented in this study, a proposed hypothesis suggests that ESG performance significantly influences the enhancement of technological innovation in privately owned businesses (non-SOEs). The proposition remains objective, concise, and employs clear language to ensure ease

of comprehension for readers. Through the analysis conducted in this study, it becomes evident that the regression coefficients associated with ESG performance exhibit comparatively larger magnitudes within industries characterized by high levels of competitiveness. This observation indicates a positive relationship between the intensity of market competition and the influential role played by ESG performance in fostering technological innovation within firms. The larger regression coefficients signify that as the degree of competition escalates within an industry, the significance of ESG performance as a catalyst for promoting firms' technological innovation becomes more pronounced.

5.4 The development stage of the company

The impact of ESG performance on a company's technological innovation may also be related to the development stage of the company. Companies in the growth stage typically carry higher investment risks. External investors tend to be more cautious due to this risk. Additionally, the financial pressure of technological innovation is greater during this stage. The importance of ESG investment is often overlooked, and there is a lack of enthusiasm for ESG information disclosure. When a company reaches the maturity period, it constantly improves its organizational structure, gains management experience, and achieves stable profits and cash flow. This enables it to meet the needs of capital and talent for technological innovation. At this time, companies pay more attention to ESG investment and information disclosure, and good ESG performance is more effective in promoting technological innovation in mature companies. To confirm the above conclusion, this study refers to Yu et al.'s (2018) research. The analyzed enterprises were divided into two groups based on their developmental stage, namely, growth and mature, depending on whether the age of the enterprise is over 10 years. Group regression was then conducted. The outcomes of this analysis can be observed in columns (7) and (8) of Table 6, in the mature enterprises, ESG performance can be more effective in improving the level of technological innovation of enterprises.

6 Conclusions and recommendations

6.1 Research conclusion

This study examines the impact of corporate ESG performance on corporate technological innovation and its mechanism of action by using panel data consisting of a total of 5,089 research samples of A-share listed companies in Shanghai and Shenzhen from 2011 to 2021. The research findings show that: (1) The capability of a company to innovate technologically is directly correlated with its ESG performance, i.e., the better the ESG performance, the more robust the company's capability. (2) ESG performance promotes corporate technological innovation through external mechanisms, such as improving corporate network location and increasing institutional ownership, on the one hand, and internal mechanisms, such as improving labor costs and easing financing constraints, on the other hand. (3) The effect of ESG performance on corporate technological innovation varies, with ESG performance favoring technological innovation more in labor-intensive businesses, privately held businesses, industries with intense competition, and businesses in the mature stage.

6.2 Policy recommendations

Drawing upon the research conclusions outlined above, this study proposes the following policy recommendations:

Firstly, this paper supports the positive role of ESG performance in technological innovation. For Chinese companies in the early stages of ESG development, it is important to recognize the significance of ESG performance. This can be achieved by taking various measures, such as actively practicing environmental protection, assuming social responsibilities, and improving corporate governance. These actions will enhance ESG performance, strengthen information communication with stakeholders, and alleviate information asymmetry issues, ultimately improving the level of technological innovation.

Secondly, companies should aim to establish a wide network of inter-company cooperation and innovation, striving to become core enterprises within the network. They should improve their information screening capabilities, avoid redundant connections, and actively establish cooperative relationships with different types of organizations. Additionally, they should optimize their ownership structure to reduce agency costs and avoid short-sighted behavior. It is also important to disclose ESG information in a timely manner to attract external financing, expand financing channels, and reduce financing costs. Finally, companies should introduce external high-end talent and cultivate internal innovative talent to stimulate employee creativity.

Thirdly, this study also confirms that labor-intensive enterprises and private enterprises are more conducive to the positive role of ESG performance in promoting technological innovation. When formulating ESG development policies, the government should establish a scientific ESG rating standard, increase the proportion of ESG information disclosure, and also classify companies. Considering the characteristics of companies comprehensively, encourage labor-intensive enterprises and private enterprises to enhance their ESG performance, amplify the promoting effect of ESG performance, and unleash the innovation vitality of enterprises.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

XZ: Conceptualization, Funding acquisition, Project administration, Supervision, Writing–review and editing. WL: Data curation, Methodology, Software, Writing–original draft, Writing–review and

editing. TJ: Formal Analysis, Visualization, Writing–review and editing. HX: Formal analysis, Visualization, Writing-review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Green finance, new infrastructure, and carbon emission performance in Chinese cities

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Green finance (GF), new infrastructure (NI), and low-carbon green development play important roles in promoting high-quality economic development in China. To date, few studies have considered the relationships among GF, NI, and carbon emission performance (CEP) simultaneously. Using the panel data of 285 Chinese cities from 2011 to 2021, an improved vertical and horizontal pull-out gearing method was used to measure the GF and NI composite indices, and the CEP was measured using the slacks-based measure (SBM) non-expected output model. Using the panel data fixed-effects model and interactive effect model, it was found that both GF and NI can effectively enhance urban CEP and produce a superposition effect, promoting each other to deepen their ability to enhance the CEP. Heterogeneity analysis showed that the effects of GF and NI are more notable in eastern China, with a higher degree of marketization, policy support for the development of the digital economy, and resource-based cities. Green technological innovation, industrial structure upgrading, and resource allocation optimization are pathways for GF and NI to jointly enhance the CEP. Further analysis of the spatial system of the equation model using the generalized three-stage least squares (GS3SLS) methodology found that there were spatial interaction spillover effects among GF, NI, and CEP and that these effects were better for a local area than for the surrounding neighboring cities.

KEYWORDS

green finance, new infrastructure, carbon emission performance, synergistic effect, spatial interaction spillovers

1 Introduction

The emission of greenhouse gases (GHGs), mainly carbon dioxide, has a profound impact on human living environments and sustainable socioeconomic development. The strategic goal of "striving to achieve carbon peaking by 2030 and carbon neutrality by 2060" is China's solemn commitment to addressing global climate change. It not only reflects China's image as a responsible and accountable big country but also fully demonstrates China's courage and determination to actively participate in global climate governance.

The promotion of a "dual-carbon" strategy is a complex systematic project that requires a large amount of financial investment. The Chinese government estimates that achieving carbon neutrality will require an investment of over 100 trillion RMB over the next 40 years (Liu et al., 2022a). However, with its existing financial capacity, China's contribution to the financial investment in carbon emission management is only approximately 15%. In the face of such a huge demand for carbon reduction funds and the pressure of economic

transformation, the remaining financial gap can only be filled by financial means, and green finance (GF) has become an inevitable choice to comply with this trend. GF is an institutional arrangement and the financial services provided to improve the environment, conserve resources and cope with climate change, and promote the development of low-carbon economy, which is important for achieving the goal of "dual-carbon" (Zhang et al., 2022a). As a new type of financial model, GF promotes the research, development, and application of green technologies; promotes the optimization of the energy structure and upgrading of the industrial structure; optimizes the allocation of resources through the support and guidance of tools, such as green loans, green bonds, green funds, and green investments; and significantly reduces carbon emissions (Gu et al., 2021; Hu et al., 2021). However, some scholars have also shown that, owing to the influence of the performance appraisal mechanism, lack of local government environmental protection supervision, information asymmetry, and other factors, GF not only fails to inhibit carbon emissions but also promotes an increase in carbon emissions (Hasman et al., 2014; Mengze and Wei, 2015; Soundarrajan and Vivek, 2016). Therefore, there is a need for further research on the relationship between GF and carbon emissions.

New infrastructure (NI) is an infrastructure construction in the context of the development of digitalization, intelligence, and networking, oriented to adapt to the needs of the new round of technological revolution and change, led by the new development concept, driven by technological innovation, based on information networks, and oriented to the need for high-quality development to provide services, such as digital transformation, intelligent upgrading, convergence, and innovation (Ministry of Industry and Information Technology, 2021). NI is an important initiative for China to lead the new economic normal, support the digital transformation of the economy and society, improve the efficiency of resource allocation, improve people's livelihoods, and enhance the people's sense of wellbeing, and it is also the key to fostering new modes, new business models, and new industries, promoting the transformation of old and new kinetic energy and the green development of the economy (Zhang et al., 2023a). The outline of the 14th Five-Year Plan for the National Economic and Social Development of the People's Republic of China and the Visionary Goals for the Year 2035 state that it is necessary to "focus on strengthening the support for digital transformation, intelligent upgrading, and convergence and innovation and to lay out and build new types of information infrastructures, convergence infrastructures, innovation infrastructures, and other new types of infrastructure." The NI has the unique advantages of being "intelligent, green, and safe," requiring "low energy consumption," and producing "low emission" and "low pollution." It is important to compensate for the shortcomings of China's industrial development and promote carbon emission reduction (Du et al., 2022). Currently, the effects of NI on carbon emissions remain controversial. In addition to supporting the view that NI is favorable for carbon emission reduction, some studies suggest that NI promotes an increase in carbon emissions (Tang and Yang, 2023). The construction of NI promotes the rapid expansion of the digital economy, which significantly increases the energy consumption for data transmission, storage, computation, applications, and device connectivity (Hintemann, 2020). NI not only emits large amounts of carbon dioxide during construction but also stimulates the consumption behavior of the population, leading to increased energy consumption and exacerbating the current carbon emission situation (Tang and Yang, 2023).

Currently, China has the largest financial market and the world's largest and most technologically advanced NI. However, it still faces major challenges in carbon emission reduction owing to its large population, the complexity of the financial market, the huge amount of capital required for NI construction, and its dependence on resources for living and production. Therefore, exploring the relationships among GF, NI, and carbon emission has become a key driver of modern economic development and an important factor in national competitiveness. As GF and NI are important elements of high-quality development, can their organic combination produce a "stacking effect" to further deepen the impact on carbon emission? What are the mechanisms underlying the relationships among GF, NI, and carbon emission? Considering the heterogeneity of regions and cities, are there any differences in the impacts of GF and NI on carbon emissions? Through which paths do they influence carbon emission?

In view of this, this study adopted panel data from 285 Chinese cities from 2011 to 2021 to explore the relationships among GF, NI, and carbon emission performance (CEP). First, this study placed GF, NI, and CEP into the same analytical framework and theoretically analyzed the mechanisms and synergistic paths of GF and NI on the CEP. The theoretical analysis showed that both GF and NI can not only directly affect CEP but also through green technology innovation, industrial structure upgrading, and resource allocation optimization. Simultaneously, they have synergistic effects that can promote each other to further deepen the effect on CEP through the "superposition effect." Second, the GF and NI composite indexes were constructed, and improved vertical and horizontal pull-out gearing methods were adopted in order to measure China's GF and NI composite indexes more comprehensively and accurately. To overcome the contradiction between the dual objectives of carbon emission reduction and economic growth, this study adopted the non-expected output SBM model to measure the CEP and indicate the level of carbon emissions. Third, we examined the general impact, synergistic effect, and transmission path of GF and NI on CEP. The results show that GF and NI can effectively improve CEP, and the conclusion still holds after the robustness test and endogeneity treatment. Their synergistic effects can also effectively improve the CEP. Green technology innovation, industrial structure upgrading, and resource allocation optimization are common paths for GF and NI to promote CEP. This study further explored the differences between GF and NI in terms of their impacts on urban CEP under heterogeneous factors, such as urban location, degree of marketization, policy support for digital economy development, and type of urban development. It was found that GF can effectively promote CEP in all regions of China with a high degree of marketization, policy support for digital economy development, and resource-based cities, whereas NI can more effectively promote CEP in eastern China with a higher degree of marketization, policy support for digital economy development, and resource-based cities. Finally, this study explored the spatial interactive spillover effects among GF, NI, and CEP. It was found that GF and NI have spatial interactive spillover effects on urban

CEP; GF can effectively promote local CEP and NI construction, as well as the CEP of neighboring cities; NI can effectively promote the CEP and GF development of local and neighboring cities; and CEP can, in turn, promote the GF development and NI construction of local and neighboring cities, and the above effects are better on the local than on the surrounding neighboring cities.

The marginal contributions of this paper are mainly as follows: (1) on the basis of clarifying the connotation of GF, NI, and CEP, we focus on the mechanism of the "superposition effect" of the impact of GF development and NI construction on CEP, analyze the synergistic effect of China's GF and NI on CEP and their complex influencing relationship, and enrich the new topic of GF and NI, leading to low-carbon development; (2) changing the characterization of previous studies using a single indicator, comprehensively measuring GF and NI levels, and adopting the non-expected output SBM model to measure CEP make the study indicators more accurate, comprehensive, and representative; and (3) a variety of econometric models were used to comprehensively analyze the general effect, synergistic effect, and spatial interactive spillover effect of GF and NI on CEP, test the common conduction paths of the two influences on CEP, and test the differences in the impacts of GF and NI on CEP in terms of regional heterogeneity, the level of marketization, the support of the digital economy development policy, the type of urban development, and other heterogeneity perspectives. These studies enrich the empirical evidence on this research topic and help promote the depth of related research.

The remainder of this paper is organized as follows: Section 2 presents the theoretical foundations and research hypotheses; Section 3 presents the research design; Section 4 presents the results of the empirical analyses, and Section 5 presents the conclusions and policy recommendations.

2 Research hypothesis

2.1 GF and CEP

The GF affects CEP mainly through the financial financing effect (Zhang et al., 2022d). Corporate environmental governance is usually characterized by a long cycle, high cost, high risk, and high uncertainty and is limited by the high innovation cost of green technology, which faces technical barriers and a shortage of funds in the process of promoting green low-carbon technology. GF, as an emerging financial model, can effectively solve the problem of matching the supply and demand of green project funds through the innovation of traditional financial instruments and provide sufficient financial guarantee for the green transformation of regional economy (Zhu et al., 2021). Therefore, this study proposes the following hypothesis:

Hypothesis 1: GF can improve CEP.

2.1.1 GF and green technological innovation

However, green technology innovation has high-risk, high-input, and long-cycle characteristics, which makes it difficult for enterprises to obtain effective support from traditional finance. Enterprises relying only on their own funds usually find it difficult to meet the needs of clean-tech production and green product development. GF can provide enterprises with long-term and stable financial support for green technological innovation through credit, funds, and other low-cost financing channels, continuously stimulate the willingness of enterprises' to invest in innovation and increase R&D, and strengthen the supervision of green technological innovation through post-credit management, thus enhancing the efficiency of green technological innovation and promoting CEP (Zhang et al., 2022c). Based on these observations, we propose the following hypothesis:

Hypothesis 1a: GF improves CEP through the green technology innovation effect.

2.1.2 GF and industrial structure upgrades

On one hand, GF can effectively cause a fund-orientation effect, provide low-cost credits through policy guidance, direct the flow of capital elements to energy-saving and environmental protection industries, promote the expansion of green industries, increase the production and consumption of clean energy, optimize the structure of energy consumption, and promote the upgrading of the industrial structure, thus achieving emission reduction effects (Wang and Wang, 2021). On the other hand, GF strictly controls the credit threshold of the main body of the enterprise, assesses the environmental risk and credit conditions of the enterprise, and, through the crowding-out effect, imposes financing constraints on high energy-consuming and high-polluting industries and enterprises, restricts the development of high-polluting enterprises, eliminates the pollution-intensive secondary industry, shifts the focus of enterprise development to the tertiary industry centered on high-tech and modern service industries, and promotes the transformation and upgrading of the regional industry so as to improve CEP (Gu et al., 2021). Based on these observations, we propose the following hypothesis:

Hypothesis 1b: GF improves CEP through the industrial structure upgrading effect.

2.1.3 GF and resource allocation optimization

GF can increase new channels of green investment in society, reduce the cost of financing, comprehensively assess the environmental standards and emission status of the financing subject through credit and post-lending links, reduce the degree of information asymmetry, use the information disclosure mechanism to have a financing penalty effect on high-pollution enterprises, and effectively exert a supervisory effect on carbon emission by the external public (Zhang et al., 2022d). Additionally, by playing the function of incentives and constraints to prompt green funds to knowledge, high-tech intensive and other green energy-saving and environmental protection industries, through the provision of diversified, multi-level, and flexible allocation of funds, optimize the allocation of resources and prompt financial institutions to participate directly in environmental governance so as to promote green and low-carbon development (Jiang et al., 2020). Therefore, this study proposes research hypothesis 1c:

Hypothesis 1c: GF improves CEP through the resource allocation optimization effect.

2.2 NI and CEP

NI breaks down the spatial and temporal restrictions and barriers between cities, which is conducive to strengthening the real-time acquisition, analysis, and judgment of urban ecological environmental data, such as CO_2, enhancing the digital control capability of carbon emissions, and reshaping the pattern of urban environmental governance (Zhang et al., 2023a). NI provides spatial attraction and impetus for socioeconomic activities and related factors, enhances the spatial expansion of urban space and internal value-adding, promotes the polycentricity of the urban spatial structure, alleviates the problem of urban diseases caused by the expansion of the urban scale and overconcentration of the population, and effectively improves CEP (Zhang et al., 2023b). NI will ultimately improve CEP by significantly increasing productivity; improving energy efficiency; developing new and cleaner resources; fostering low-energy production; promoting e-mobility, smart cities, teleworking, and distance learning; encouraging individuals to use digital devices to shape their consumption patterns and behaviors; and changing their production and lifestyles (Zhang et al., 2023a; Tang and Yang, 2023). In general, the increase in carbon emissions due to NI construction is temporary, and the impact on carbon reduction is long-lasting. With the increasing maturity of digital technology and its operation, its own carbon emissions become limited, and overall, NI can effectively improve CEP (Yang et al., 2022). Therefore, this study proposes hypothesis 2:

Hypothesis 2: NI can improve CEP.

2.2.1 NI and green technological innovation

NI supported by digital technology can significantly reduce the cost of information search, transmission cost, and knowledge dissemination cost; accelerate the diffusion of technology and knowledge overflow; accelerate the integration of technology and industry; deepen regional cooperation; enhance the level and efficiency of regional innovation; innovatively stimulate enterprises to increase R&D investment; and promote enterprise independent innovation and industrial collaborative innovation (Xu et al., 2019). NI provides the visual instant communication environment and provides conditions for full spillover of technological knowledge (Xie et al., 2021). Based on this, we propose the following hypothesis:

Hypothesis 2a: NI improves CEP through the green technological innovation effect.

2.2.2 NI and industrial structural upgrades

NI endows machines and equipment with powerful learning and computing capabilities; makes capital present digital and intelligent trend construction; drives industrial digital development and digital industrialization transformation; promotes the synergistic development of software and hardware of AI, data center, cloud computing, and other application scenarios; and assists enterprises in their digital transformation by stimulating technological innovation, expanding knowledge spillover, and optimizing the market environment (Ren et al., 2021). NI promotes the development of industrial structures toward high-precision industries and the elimination of backward industries by improving technology, substituting labor with capital, promoting the dissemination of regional knowledge and technology, improving core competitiveness, improving the efficiency of production factors, and accelerating the high-end processes of industries, thus effectively improving the level of CEP (Wang et al., 2023). Accordingly, we propose the following hypothesis:

Hypothesis 2b: NI improves CEP through the industrial structure upgrading effect.

2.2.3 NI and resource allocation optimization

NI, with big data, artificial intelligence, industrial Internet, and other technological advantages, fundamentally breaks through the spatial obstacles to the flow of factors in the arithmetic and algorithms to promote the various types of data elements that can be fully circulated in the market, to overcome the drawbacks caused by the asymmetric information, and to improve the efficiency of resource allocation through the investment multiplier effect, the industrial optimization effect, the network demonstration effect, and the spatial spillover effect (Bakken, 2019). In addition, the integration of NI and traditional industries can improve the combination of inputs of different production factors in the real economy, reduce the probability of factor mismatch, achieve efficient allocation and use of factor resources, and thus, effectively improve the level of CEP (Martínez et al., 2022). Accordingly, we propose the following hypothesis:

Hypothesis 2c: NI improves CEP through the resource allocation optimization effect.

2.3 GF, NI, and CEP

The effective integration of NI centered on big data, cloud computing, blockchain, 5G, and other digital technologies with the financial system can effectively support the operational efficiency of the financial system, reduce the operating costs of financial institutions, improve the asymmetry of information and the matching of supply and demand in the financial market, expand the market's supply potential, improve the efficiency of capital allocation, and promote the agglomeration of financial resources (Zhang et al., 2022d). The development of digital technology promoted by NI can regulate and ensure the targeted input of funds, effectively optimize the review process and supervision mechanism of various investment projects, reduce the systematic risk of financial institutions and the risk of investment across time, form an effective and stable financial system, and promote the green development of the local economy (Yang et al., 2022).

NI is an urban infrastructure representing a new round of technological and industrial revolution and is an important embodiment of capital. NI construction is characterized by high capital demand, a long investment cycle, high fixed cost and low marginal cost, and high degree of market operation, which require diversified subjects to participate in the investment and construction (Zhang et al., 2023a). In addition to government investments, most

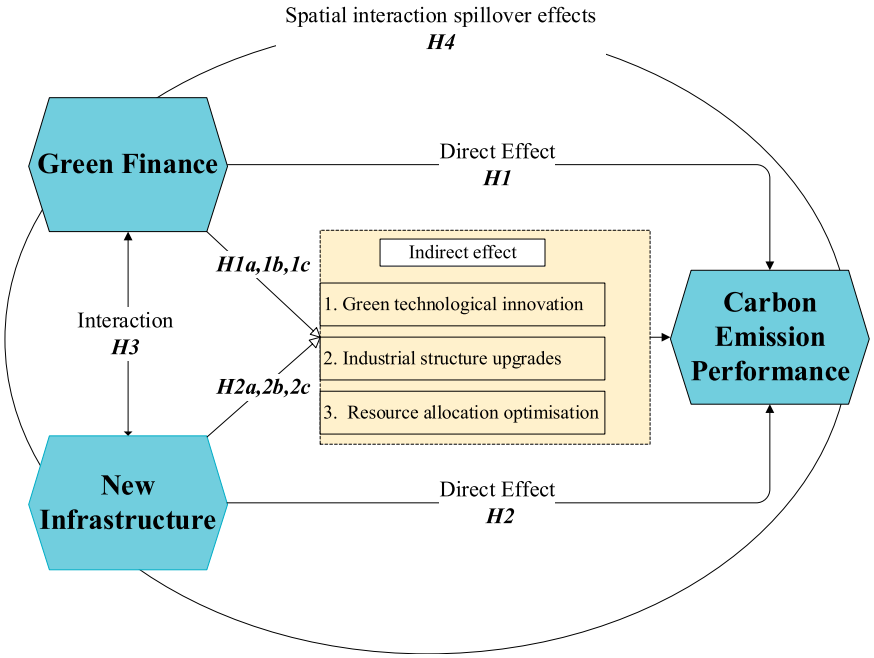


FIGURE 1
Mechanism analysis of green finance (GF) and new infrastructure (NI) affecting carbon emission performance (CEP).

funds must be obtained through market-oriented approaches. As a new financial model, through policy and market mechanism design, it can have a social capital mobilization effect, guide the social capital layout of the green industry, and alleviate NI construction financing problems. Only when supported by sufficient funds can NI construction gradually improve to play the advantage of zero-cost diffusion, which can effectively play a low-carbon green role (Raheem et al., 2020).

The aforementioned analyses show that GF and NI not only contribute to CEP but also interact with each other to improve CEP. Therefore, the following research hypothesis is proposed:

Hypothesis 3: GF and NI interact with each other and synergistically improve CEP.

2.4 Spatial interaction spillover effects

Notably, GF and NI can transcend spatial limitations, not only affecting local cities but also extending their impacts to neighboring cities as well (Zhang et al., 2022d; Zhang et al., 2023a). The development of GF and NI in local cities not only improves the CEP of local cities but also shows potential to affect the CEP level of surrounding neighboring cities (Zhang et al., 2024). In addition, gases are mobile, and GHGs are no exception; CO_2 can flow between different regions with clear spatial dependence (Li and Li, 2020). Cities imitate each other in the process of development and learn from each other's advanced urban management experiences, and cities in the same region show the same development characteristics (Liu et al., 2022b). In addition, Section 2.2 shows that GF and NI can interact with and mutually reinforce each other, thereby improving CEP through the synergistic stacking effect. It is worthwhile considering whether the change in the level of urban carbon emissions may, in turn, influence the formulation of urban development policies, in particular the GF development policy and the speed of NI construction. In turn, CEP affects GF and NI. Therefore, hypothesis 4 is proposed.

Hypothesis 4: GF, NI, and CEP have spatial interaction spillover effects.

The specific mechanism of action is shown in Figure 1.

3 Research design

3.1 Model

Based on the extended STIRPAT model, this study adopted city–year fixed effects to study the impacts of GF and NI on CEP and constructed the following model:

$$CEP_{it} = \alpha_0 + \alpha_1 GF_{it} + \alpha_2 NI_{it} + \beta_n \sum X_{it} + \mu_i + \gamma_t + \varepsilon_{it}, \quad (1)$$

where CEP denotes the city CEP; GF denotes the city GF development level; NI denotes the combined level of NI construction in the city; X is the remaining control variable; μ_i and γ_t denote the city and year fixed effects, respectively; and ε_{it} denotes the vector of random errors.

In this study, model 2 was constructed to examine the synergistic effects of GF and NI on CEP.

$$CEP_{it} = \alpha_0 + \alpha_1 GF_{it} + \alpha_2 NI_{it} + \alpha_3 GF_{it} \times NI_{it} + \beta_n \sum X_{it} + \mu_i + \gamma_t + \varepsilon_{it}. \quad (2)$$

If $\alpha_3 > 0$ holds in model 2, then GF and NI have synergistic effects and can promote each other to synergistically affect CEP; thus, hypothesis 4 is valid.

TABLE 1 GF indicator system.

Primary index	Secondary index	Tertiary index
Green finance	Green credit	Percentage of interest expenses of six energy-intensive industries = interest expenses of energy-intensive industries/industrial interest expenses
	Green securities	Market capitalization of energy-saving and environmental protection enterprises = market capitalization of energy-saving and environmental protection enterprises/total market capitalization of the company
		Market capitalization share of the six energy-intensive industries = market capitalization of energy-intensive companies/total company market capitalization
	Green insurance	Agricultural insurance payout ratio = agricultural insurance expenditure/agricultural insurance receipts
		Agricultural insurance scale = agricultural insurance expenditure/total insurance expenditure
	Green investment	Share of public expenditure on energy conservation and environmental protection = financial expenditure on energy conservation and environmental protection/GDP
		Percentage of investment in environmental pollution control = amount of investment in pollution control/GDP

In this study, we also constructed the following spatial system of the simultaneous equation model to consider the spatial interaction spillover effects among GF, NI, and CEP:

$$\begin{cases} CEP_{it} = \alpha_0 + \rho_1 W_{ij} CEP_{jt} + \alpha_1 GF_{it} + \alpha_2 NI_{it} + \alpha_3 W_{ij} GF_{jt} + \alpha_4 W_{ij} NI_{jt} + \alpha_n \sum X_{it} + \mu_1 + \gamma_1 + \varepsilon_1 \\ GF_{it} = \beta_0 + \rho_2 W_{ij} GF_{jt} + \beta_1 NI_{it} + \beta_2 CEP_{it} + \beta_3 W_{ij} NI_{jt} + \beta_4 W_{ij} CEP_{jt} + \beta_n \sum X_{it} + \mu_2 + \gamma_2 + \varepsilon_2, \\ NI_{it} = \delta_0 + \rho_3 W_{ij} NI_{jt} + \delta_1 GF_{it} + \delta_2 CEP_{it} + \delta_3 W_{ij} GF_{jt} + \delta_4 W_{ij} CEP_{jt} + \delta_n \sum X_{it} + \mu_3 + \gamma_3 + \varepsilon_3 \end{cases} \tag{3}$$

where ρ represents the spatial lag regression coefficient; $j(j \neq i)$ denotes neighboring cities around city i; and W_{ij} is the spatial weight matrix. This study uses a spatial economic geographical matrix. When $i \neq j$ and regions i and j share a common boundary, $W_{ij} = e_i / \sum_{s \in J} x_s$; otherwise, $W_{ij} = 0$, where e denotes the regional economic development level (GDP), s denotes the region, and J is the set of all districts with adjacent borders to city i.

3.2 Variables

3.2.1 CEP

In the study of carbon emission indicators, total carbon emissions, carbon emission intensity, and CEP are typically used. However, with the transformation of China's economic development paradigm and the tightening of energy and environmental constraints, relying solely on a single-factor carbon productivity indicator (i.e., GDP per unit of carbon emissions) fails to capture the intricate reality of current economic and social progress. Compared with the total carbon emission indicators, CEP integrates various input factors and is a more comprehensive measure that includes the factors of economic development, which is the result of the combined effect of the energy structure and factor substitution, and can be interpreted as the total factor CEP (Zhang et al., 2022d). Therefore, CEP was selected as a measure of carbon emission in this study. CEP was calculated using the SBM non-expected output model proposed by Tone (2020), where the input variables were labor, capital, and energy; the expected output was GDP; and the non-expected output was CO_2 emissions.

3.2.2 GF

According to the Guiding Opinions on Constructing the GF System (2016, No. 228), GF mainly comprises green credit, securities, insurance, and investments (Zhang et al., 2022d). Referring to existing studies and considering the actual development of GF in China and data availability, four dimensions of green credit, green securities, green insurance, and green investment, and six basic indicators were selected to construct the evaluation index system of the GF development level (Zhang et al., 2022b; Zhang et al., 2022d). The details are presented in Table 1.

To eliminate inconsistencies in the order of magnitude and scale, the raw data were first standardized using the extreme variance method. Then, an improved vertical and horizontal pull-out gearing method was used to calculate the GF development index for each region during the sample period.

3.2.3 NI

The 2020 China Development and Reform Commission pointed out that NI primarily includes three aspects: information infrastructure, convergence infrastructure, and innovation infrastructure. Compared to single indicators, such as the number of Internet accesses, composite indicators can integrate multiple indicator characteristics that are more representative and theoretically significant. Starting from the connotation of NI, basic indicators, such as broadband Internet base, mobile Internet base, telecommunication base, and information and software scale, were selected to construct the index system for measuring new infrastructure (Zhao and Sun, 2022; Zhang et al., 2023a). The same vertical and horizontal slotting methods were used to assign weights to calculate the composite index (Table 2).

3.2.4 Remaining key control variables

Referring to Zhang et al. (2022d), Zhang et al. (2023a), and Tang and Yang (2023), this study controlled other potential factors that may affect CEP. They mainly included economic development, energy consumption, population density, industrial structure, technological inputs, openness, and urbanization level. Economic development was measured using regional GDP *per capita*. The total carbon emissions were estimated based on the consumption of

TABLE 2 NI indicator system.

Primary index	Secondary index	Tertiary index
New infrastructure	Broadband Internet infrastructure	Number of Internet broadband access subscribers
	Mobile Internet fundamentals	Number of mobile phone users
	Telecommunications infrastructure	Revenue from telecommunications services
	Information and software scale	Number of information transmission computer services
		Software industry practitioners

TABLE 3 Descriptive statistics for each variable.

Variable	Symbol	Mean	SD	Minimum	Maximum
CEP	CEP	0.687	0.175	0.325	1.501
GF	GF	0.187	0.109	0.070	0.749
NI	NI	0.156	0.727	0.061	0.759
Technical input	TEC	4.471	1.154	1.760	9.511
Forest cover	GREEN	0.340	0.18	0.040	0.670
Openness level	OPEN	0.270	0.289	0.007	1.443
Industrial structure	INDU	0.479	0.105	0.111	0.893
Energy consumption structure	STRU	0.730	0.305	0.197	2.517
Urbanization rate	CRTY	0.580	0.120	0.340	0.900
Regional economic level	PGDP	8.671	3.754	19.381	37.558
Level of government intervention	GOV	0.264	0.115	0.119	0.758

14 fossil energy sources in the Energy Balance Sheet of the China Energy Statistics Yearbook, using the reference methodology and default parameters provided by the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and combining them with the relevant parameters officially announced by China. The technology level was measured using *per capita* financial expenditure on science and technology. The forest coverage rate was measured as the ratio of the forest area to the urban land area. The urbanization rate was measured as the ratio of the urban population to the total population of the region. The degree of regional openness was measured using the ratio of the overall regional imports and exports to the regional GDP. The degree of government intervention was measured using the ratio of the fiscal expenditure of the regional government to the regional GDP.

3.3 Data

The implementation effect of policies often depends on strict constraints and the effective implementation of policies in prefectural cities; therefore, a study using a large sample of prefectural cities can objectively and effectively evaluate the implementation effect of the relevant "dual-carbon" policies formulated by the central government, as well as the provinces and municipalities. In this study, a panel of 285 cities in China from 2011 to 2021 was selected for empirical analysis (excluding regions with missing data). The data were mainly collected from all relevant statistical yearbooks and local statistical bureaus, as well as from the EPS, CSMAR, WIND, relevant websites, and the Internet. Missing data for cities in individual years were filled using linear interpolation. Descriptive statistics for each variable are shown in Table 3.

4 Empirical results and analyses

4.1 Benchmark regression results

In this study, the mean variance inflation factor (mean VIF) was used to test the model for multicollinearity, and the test results showed that none of the values exceeded the critical value of 10; therefore, it can be judged that the model variables do not have strict multicollinearity problems. Using the F-test and Hausman test, this study selected the panel data fixed-effects model for testing. The results of the benchmark regression are shown in Table 4.

In Table 4, regression result (1) shows the effect of considering only GF on CEP. The regression coefficient of GF and CEP was 0.3757 and significant at the 1% significance level, indicating that GF can effectively enhance CEP. The test results supported H1. The reason for this is that the most basic function of the GF is to raise and allocate funds so that financial resources can enter the field of green and low-carbon development in a more effectively way by optimizing the allocation of resources, encouraging green

TABLE 4 Benchmark regression results.

	(1)	(2)	(3)	(4)	(5)
					0.6512***
					(11.51)
GF	0.3757***		0.2145***	0.2051***	0.1085***
	(4.32)		(4.51)	(4.61)	(5.12)
NI		0.1579**	0.1621***	0.1684***	0.0951***
		(2.31)	(3.25)	(3.64)	(4.52)
PGDP	0.4232	0.2954	0.3021	0.3054	0.4211
	(1.24)	(1.15)	(0.05)	(0.05)	(1.09)
STRU	−0.1542***	−0.1421***	−0.2516***	−0.2601***	−0.0821***
	(-3.51)	(-4.09)	(-3.21)	(-3.26)	(-2.99)
INDU	−0.2147***	−0.2801***	−0.2458***	−0.2460***	−0.1024***
	(-4.21)	(-3.91)	(-3.51)	(-3.62)	(-5.01)
TEC	0.5521***	0.5012***	0.5123***	0.5127***	0.2941***
	(4.95)	(4.21)	(3.96)	(3.87)	(5.12)
OPEN	0.0475**	0.0419**	0.0512***	0.0541***	0.0214***
	(2.23)	(2.41)	(2.65)	(2.71)	(3.51)
CITY	−0.0784	−0.0751	−0.0651	−0.0708	−0.1051*
	(-1.24)	(-1.60)	(-1.61)	(-1.64)	(-1.87)
GREEN	0.0247***	0.0254***	0.0241***	0.0240***	0.0147***
	(4.51)	(4.62)	(4.55)	(4.55)	(7.51)
GOV	0.1547***	0.1544***	0.1544***	0.1543***	0.2104***
	(5.87)	(5.79)	(5.78)	(5.14)	(7.81)
GF × NI				0.0521***	
				(5.15)	
Cons	9.9276***	10.5167***	8.9514***	9.5712***	−2.6547***
	(12.36)	(11.62)	(12.64)	(13.57)	(-18.15)
AR (2)					3.0621
					(0.4125)
Saegan					149.64
					(0.8746)

Note: $^{***}p < 0.01$, $^{**}p < 0.05$, and $^{*}p < 0.1$; t-statistics are given in parentheses.

innovation, guiding the shift of enterprise production patterns to low-carbon and environmentally friendly patterns, and improving energy efficiency, thus enabling a significant increase in the CEP (Song et al., 2021; Zhang et al., 2022d).

The regression result (2) showed the effect of considering only the effect of NI on CEP. The regression results showed that NI construction is also effective in improving CEP, which is in line with research hypothesis 2. NI construction enables the government to accurately and efficiently obtain data related to carbon emissions to formulate appropriate carbon emission reduction measures (Zhang et al., 2022a). Moreover, NI benefits enterprises by optimizing resource allocation and upgrading production processes, thereby improving CEP (Martínez et al., 2022). In addition, NI reshapes consumers' green awareness through the network and changes consumption patterns, thereby promoting low carbon consumption (Nudurupati et al., 2022). Therefore, NI can effectively influence the behavior of governments, enterprises, and residents, thus promoting the level of urban CEP.

Regression result (3) showed the effects of both GF and NI on CEP. The regression results showed that both GF and NI could effectively increase CEP levels. From the perspective of the control variables, the elasticity coefficient of GDP *per capita* was positive but

TABLE 5 Robustness test results.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
GF	0.3102***		0.3081***	0.3907***		0.3171***	−0.2372***
	(4.13)		(4.07)	(6.87)		(5.367)	(-3.52)
NI		0.0954***	0.0792***		0.2087***	0.2117***	−0.2253***
		(4.17)	(3.58)		(3.72)	(3.421)	(-4.31)
Controls	YES	YES	YES	YES	YES	YES	YES

Note: $^{***}p < 0.01$, $^{**}p < 0.05$, and $^{*}p < 0.1$; t-statistics are given in parentheses.

TABLE 6 Endogeneity test results.

	GF	CEP	NI	CEP	CEP	CEP
	(1)	(2)	(3)	(4)	(5)	(6)
GF		0.1734***				
		(2.87)				
L. GF					0.1972***	
					(11.57)	
NI				0.0514***		
				(3.94)		
L. NI						0.0817***
						(20.87)
IV	0.0172***		0.0153***			
	(4.23)		(4.59)			
Controls	YES	YES	YES	YES	YES	YES
LM		32.846***		21.841***	110.541***	247.87***
F		50.65***		15.39***	330.15***	547.41***

Note: $^{***}p < 0.01$, $^{**}p < 0.05$, and $^{*}p < 0.1$; t-statistics are given in parentheses.

not significant, indicating no notable relationship between economic growth and carbon emissions. The regression coefficient between the energy consumption structure and CEP was significantly negative because coal-based fossil fuel combustion remained one of the main sources of carbon emissions in China. The industrial structure also significantly reduced CEP, suggesting that an industrial structure dominated by secondary industries will exacerbate carbon emissions and reduce CEP; therefore, transformation of the industrial structure is urgent. The regression coefficient between technological innovation and CEP was significantly positive. Green technological innovation, represented by green invention, effectively reduces energy consumption through technological transformation and clean production mode, which, in turn, increases CEP (Xie et al., 2021). The regression coefficient between regional openness and CEP was significantly positively correlated. Regions with a high degree of openness were more inclined to absorb green investment and obtain advanced management experience and green innovation technology, which are conducive to CEP enhancement.

In regression result (4), we constructed the cross-term between GF and NI to test the effect of the interaction between GF and NI on CEP. The significant positive correlation between the cross-terms and regression coefficients of CEP show that the two can coordinate with each other, produce a superposition effect, and enhance the ability to improve CEP. On one hand, NI can promote GF to better play its role in capital financing and information disclosure and then promote the urban CEP; on the other hand, GF can provide sufficient funds to support the construction of NI and improve the urban NI and then play its role in information transmission, green innovation, resource saving, and efficiency enhancement, and thus, enhance the CEP (Zhang et al., 2022d; Zhang et al., 2023a). This finding is also in line with research hypothesis H3.

Because the core explanatory variables of this study, urban GF and NI construction levels, use a synthetic composite indicator, the regression estimation using only the panel data fixed-effects model may be biased. Regression result (4) is the result of the regression analysis using the systematic method of moment estimation to consider the robustness of the regression results and avoid the

effect of endogeneity. The generalized method of moment (GMM) estimation is a commonly used method for solving the model endogeneity problem and is divided into differential GMM (DIF-GMM) and systematic GMM (SYS-GMM). Among them, SYS-GMM combines the DIF-GMM model and the horizontal GMM model, which can improve the estimation efficiency compared with DIF-GMM estimation (Liu and He, 2019). The system generalized moment estimation regression results show that the GF and NI constructions can still effectively improve the CEP.

4.2 Robustness tests

In this study, three main methods were used: the entropy weight method was used to re-measure GF and NI, the regression of GF and NI with a one-period lag was used, the core explanatory variables were replaced, and CO_2 emission intensity was used instead of CEP. The robustness test results are presented in Table 5.

Regression results (1)–(3) show the regression results of the remeasured GF and NI indices using the entropy method. Column (1) shows the results of the regression of the newly measured GF, column (2) shows the results of the regression of the newly measured NI, and column (3) shows the results of the regression analyses of both using the newly measured indicators. As shown in Table 5, the regression results using the new indicators indicate that both GF and NI were effective in increasing CEP levels.

Regression results (4)–(6) show the regression results of the lagging GF, NI, and both for one period. The regression results showed that GF and NI can still effectively improve CEP after adopting the lagged one-period variables, and the size of the regression coefficients show that the regression results of the lagged variables are larger, which indicates that the effect of GF and NI on CEP has a certain lag, and the green and low-carbon efficacy of both needs a certain amount of time to transform (Raheem et al., 2020).

Regression result (7) showed the regression result after replacing CEP with carbon emission intensity. The results showed that GF and NI can effectively contribute to a reduction in carbon emission intensity, thus verifying the robustness of the results.

4.3 Endogeneity treatment

Although this study attempted to control the factors affecting CEP, the empirical results may still be affected by a number of unobservable factors. To mitigate endogeneity problems due to omitted variables, measurement errors, and reverse causality, this study used instrumental variable estimation methods for endogeneity (Table 6).

(1) GF endogeneity. The degree of financial market sophistication is closely related to GF development, while the number of historical banking institutions can reflect the basis of current financial development, which, in turn, is related to the level of GF development (Zhang et al., 2022d). Considering that a time-varying trend was observed in the development of GF and that the number of banking institutions in history was cross-sectional data, the interaction term of the number of branches of banking institutions in 1935 multiplied by the green coverage rate of each city lagged by three periods was used as an instrumental variable, and the two-stage instrumental variable method was chosen to deal with endogeneity. The selection of instrumental variables must fulfill the two conditions of correlation and exogeneity. The more business outlets banking financial institutions have in each region, the more convenient it is for enterprises to obtain credit. In addition, cities with more business outlets of financial institutions are generally located in economically developed regions, where the government pays more attention to environmental quality, which helps guide credit funds to green and low-carbon development industries and reduces credit fund support for high energy-consuming and high-emission enterprises (Zhang et al., 2022b). Therefore, it is highly correlated with carbon emissions. In addition, the greening coverage of built-up areas reflects the local green awareness; the stronger the green awareness, the smoother the GF development, which satisfies the correlation hypothesis. Moreover, greening coverage is not directly related to pollutants and carbon dioxide emissions, which is also exogenous. Therefore, it satisfies the strict exogeneity of the instrumental variables. The instrumental variable regression results show that GF has a significantly positive effect on CEP, which is consistent with the baseline results.

(2) NI endogeneity. Referring to the study by Zhang et al. (2023a), who adopted traditional infrastructure variables as instrumental variables of NI, this study selected the interaction term between the number of letters sent *per capita* and the number of Internet broadband users in 2000 as the instrumental variable. The "new" is relative to traditional infrastructure, and its essence is still infrastructure. The number of letters sent represents several elements in the context of traditional infrastructure, such as the level of logistics in each region, the number of staff in the relevant industries, and postal revenue, representing the predecessor of digital infrastructure. The instrumental variable data selected in this paper were 2,000, which is far from the sample data of this study, while the number of letters sent has almost no time effect (Zhang et al., 2023a). Therefore, it had no significant effect on CO_2 and satisfied the exogenous condition. The instrumental variable regression results showed that NI had a significant positive effect on CEP, which is consistent with the benchmark results.

In addition, with reference to the study by Hu et al. (2023), this study also selected one-cycle lag GF and NI as instrumental variables. Using data lagged by one cycle, a direct association with the current cycle was ensured while avoiding a direct link with the current cycle variable. This approach is consistent with exogeneity. The regression results in columns (5) and (6) of Table 6 are consistent with those in the previous section.

TABLE 7 Heterogeneous effects of GF and NI on urban CEP.

	Eastern	Midwest	High market	Low market	Policy support	Ordinary city	Resource city	Non-resource city
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
GF	0.2102***	0.0345**	0.2022***	−0.1347**	0.1762***	0.0633*	0.1975***	0.1514
	(6.13)	(6.86)	(3.07)	(-5.88)	(4.14)	(1.76)	(5.82)	(3.28)
NI	0.0793***	0.0261	0.0164***	0.0125	0.1578***	0.0745	0.1957***	0.4647
	(4.03)	(1.01)	(4.18)	(1.51)	(4.72)	(0.731)	(6.71)	(1.47)
Controls	YES	YES	YES	YES	YES	YES	YES	YES
Observations	1,111	2,024	1,566	1,569	374	2,761	1,859	1,276
P-GF	0.031*		0.025***		0.036*		0.126***	
P-NI	0.098***		0.051***		0.108***		0.057***	

Note: $^{***}p < 0.01$, $^{**}p < 0.05$, and $^{*}p < 0.1$; t-statistics are given in parentheses. P is the result of the intergroup coefficient difference test conducted using the bootstrap method to extract samples 1,000 times.

TABLE 8 Mechanism test of green technology innovation.

Variant	(1)	(2)	(3)	(4)
TI	0.0329**	−0.0523**	−0.097*	0.0127
	(2.33)	(-2.31)	(-1.78)	(1.06)
GF		0.2439***		0.2627*
		(5.64)		(1.87)
NI			0.1258***	0.1035***
			(2.97)	(3.17)
GF × TI		0.1226***		−0.4217
		(2.97)		(-0.79)
NI × TI			0.0235**	−0.0141*
			(2.39)	(-1.71)
GF × NI × TI				0.0826**
				(2.09)
Controls	YES	YES	YES	YES

Note: $^{***}p < 0.01$, $^{**}p < 0.05$, and $^{*}p < 0.1$; t-statistics are given in parentheses.

4.4 Heterogeneity analysis

The impacts of GF and NI on CEP vary across Chinese cities owing to great differences in resource endowment, city size, and geographical location (Zhang et al., 2023b). In this study, we tested the heterogeneous effects of GF and NI on the impact of CEP according to heterogeneous factors, such as geographic location, market maturity, policy support for digital economy development, and type of urban development (Table 7).

(1) Geographic location of cities. Based on the criteria of the National Bureau of Statistics of China for dividing China into three major regions, the sample was divided into eastern, central, and western cities. The regression results are shown in columns (1) and (2) in Table 7. Among these, GF effectively promoted CEP in the eastern, central, and western cities of China. However, by analyzing the size of the regression coefficients, GF is more effective in promoting the CEP of eastern cities. Simultaneously, NI can effectively promote the CEP of the eastern cities, but its effect on the CEP of the central and western cities is not significant. The significance test of the difference in coefficients revealed that the *p*-values of the regression coefficients of GF and NI among the eastern, central, and western regions were 0.031 and 0.098, respectively, and significant at the 10% and 1% significance levels, respectively. This indicates a significant difference in the regression coefficients among the eastern, central, and western regions. Currently, cities in eastern China have a

TABLE 9 Mechanism test for industrial structure optimization and upgrading.

Variant	(1)	(2)	(3)	(4)
IU	0.3122***	−0.3031	0.0271	0.2189
	(7.09)	(-1.31)	(0.69)	(0.76)
GF		0.2135***		0.3204***
		(3.12)		(3.87)
NF			0.1391**	0.2210*
			(3.41)	(2.17)
GF × IU		0.2146***		0.1424**
		(4.15)		(2.51)
NI × IU			0.3201***	−0.2916**
			(4.90)	(-2.11)
GF × NI × IU				0.2117***
				(3.09)
Controls	YES	YES	YES	YES

Note: ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$; t-statistics are given in parentheses.

TABLE 10 Mechanism test for resource allocation optimization.

Variant	(1)	(2)	(3)	(4)
RA	0.1521***	0.2313*	0.1274***	0.0197***
	(3.14)	(1.74)	(3.69)	(2.41)
GF		0.1224*		0.2241*
		(2.12)		(1.87)
NI			0.3211*	0.1302
			(1.71)	(1.17)
GF × RA		0.0314**		−0.2122***
		(2.15)		(-3.51)
NI × RA			0.2315***	−0.1201
			(4.91)	(-1.11)
GF × NI × RA				0.2521***
				(3.59)
Controls	YES	YES	YES	YES

Note: ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$; t-statistics are given in parentheses.

more complete digital infrastructure and stricter environmental protection measures, better human capital, a strong awareness of low-carbon and environmental protection among residents, and a greater demand for low-carbon products, forcing GF and NI to support the development of low-carbon projects and product production (Zhang et al., 2023b). However, the economic structure of the central and western regions lags behind that of the eastern regions, and traditional industries account for a high proportion; therefore, the influence of GF and NI on urban CEP is still in the primary stage. Moreover, the pressure of economic development is greater in the central and western regions, which are more willing to focus on economic construction than on reducing carbon emissions (Zhang et al., 2023a).

(2) Marketization level. Referring to the marketization index compiled by Fan et al. (2010), based on the median of the index, the sample is divided into cities with a "high level of market intermediary organization development" and cities with a "low level of market intermediary organization development." GF and NI have a significant positive effect on CEP at a high level of market intermediary organizational development, whereas GF exerts a significant negative effect on CEP at a low level. The effect of the NI on CEP in low markets is not significant. The test of significance of the difference in coefficients showed a significant difference in the regression coefficients between the two groups. The industrial structure and green technology innovation effects of GF and NI are stronger in markets where GF and NI have a more robust market intermediary organization development and are more effective on CEP (Hu et al., 2021). The above study shows that the difference in the development of market intermediary organizations significantly influences the effects of GF and NI on CEP.

(3) Policy support for urban digital economy development. According to China's smart city "white paper" and big data comprehensive pilot zone division standards, pilot cities are mostly cities with higher administrative levels in each province. Therefore, according to the list of China's smart city pilot units and the national administrative level, this study defined pilot cities, municipalities, provincial capitals, and sub-provincial cities as cities with policy support for the development of the digital economy and the rest of the cities as ordinary cities. Generally, high-level cities are more active in market economy and infrastructure development than general cities (Zhang et al., 2023b). The results of the grouped regression are shown in columns (4) and (5) of Table 7. Among them, both GF and NI in high-level cities enhanced urban CEP at the 1% significance level, whereas in ordinary cities, GF only enhanced urban CEP at the 10% significance level, and NI did not have a significant effect on urban CEP. The test of significance of the difference in coefficients showed a significant difference in the regression coefficients between the two groups. This is because high-level cities can enjoy more policy favors from the state and are more sensitive to the development of the digital economy, and the green effects of GF and NI are more effective (Zhou et al., 2021).

(4) Urban development types. The economic development of resource-based cities is dominated by industries involved in the extraction and processing of natural resources. According to China's National Sustainable Development Plan for Resource-Based Cities (2013–2022), the city sample was divided into resource-based and non-resource-based cities. The regression results in columns (8) and (9) show that GF and NI can effectively increase CEP in resource-based cities, whereas in non-resource-based cities, the effects of GF and NI on CEP are not significant. The test of significance of the difference in coefficients showed a

TABLE 11 Regression results of spatial interaction spillover effects of GF, NI, and CEP.

	CEP	GF	NI
	(1)	(2)	(3)
CEP		0.0439*** (5.16)	0.0125** (2.51)
GF	0.3277*** (4.32)		0.5179*** (7.12)
NI	0.0378*** (5.12)	0.0721*** (4.92)	
W × CEP	0.7406** (2.04)	0.0122** (2.41)	0.0023* (1.71)
W × GF	0.1229** (2.31)	0.8636*** (4.26)	−0.0534** (−1.99)
W × NI	0.0092** (2.09)	0.0017* (1.91)	0.4027** (2.77)
PGDP	0.2440 (1.03)	0.1425*** (4.54)	0.4121*** (9.74)
STRU	−0.1263*** (−4.14)	0.0827* (1.74)	0.1147*** (3.18)
INDU	−0.1748*** (−4.21)	0.1427*** (3.34)	0.0194** (2.53)
INO	0.4127*** (4.08)	0.2417*** (5.18)	0.1389*** (5.12)
OPEN	0.0231*** (3.23)	0.1727*** (4.12)	0.2074*** (3.57)
CITY	−0.0724 (−1.24)		0.2104* (1.66)
GOV	0.1537*** (5.87)	0.0844** (2.34)	0.1912*** (3.12)
GREEN	0.0224*** (4.51)		

Note: $^{***}p < 0.01$, $^{**}p < 0.05$, and $^{*}p < 0.1$; t-statistics are given in parentheses.

significant difference in the regression coefficients between the two groups. This indicates that GF and NI are more effective in enhancing CEP in traditional resource-based cities. Traditional resource-based cities rely on energy-intensive and highly polluting industries related to traditional resources, resulting in high carbon emissions (Che and Wang, 2022). GF and NI play key roles in helping resource-based cities upgrade the existing industrial model, promote transformation and upgrading, and reduce carbon emissions (Bakken, 2019).

4.5 Underlying mechanisms

4.5.1 Technological innovation

The technological innovation (TI) effect refers to the use of digital technologies, such as Internet technology, big data analysis, and artificial intelligence, to innovate and optimize the industrial development model (Zhao et al., 2023). This effect can be used in production and life to promote the target subject to carry out green-based technological innovation, which, in turn, improves the resource utilization rate to reduce the pollution emission in production and life or improves the pollutant treatment technology and efficiency, which, in turn, improves CEP (Xie et al., 2021). In this study, the level of green technological innovation was expressed and specifically measured by the ratio of the number of granted green patents to the total number of patent applications in the year (Zhang et al., 2023a). The regression results are presented in Table 8.

Column (1) shows that green technological innovation had a significantly positive effect on CEP. Column (2) shows that the GF and green technological innovation cross-multiplier term were significant at the 1% level, indicating that GF can strengthen the enhancement effect of green technological innovation on CEP, which is consistent with the theoretical analysis in the previous section. Column (3) shows that the estimated coefficient of NI and the green technological innovation cross-multiplier term were significantly positive at the 5% significance level, which indicates that NI is an important moderating variable of green technological innovation affecting CEP. The regression coefficient of GF × NI × TI in column (4) was also significantly positive at the 5% significance level, and combined with the positive regression results of green technological innovation and CEP in column (1), it can be observed that the construction of GF and NI can jointly promote CEP enhancement through the green technological innovation channel. In addition, comparing the size of the regression coefficients of the TI term in column (1) and the GF × NI × TI term in column (4), we found that the regression coefficients of the latter term were large, indicating that the synergistic effects of GF and NI significantly enhanced CEP promotion through green technological innovation. These results are consistent with hypotheses 1a and 1b.

4.5.2 Industrial structure upgrading

Industrial upgrading (IU) implies that highly polluting and energy-consuming industries will be eliminated, strategic emerging industries and modern service industries will be accelerated, pollutant emissions such as carbon dioxide and soot in production will be reduced, and production and consumption patterns will become more sustainable (Gu et al., 2021). Specifically, the industrial upgrading index is calculated by assigning weights of 1, 2, and 3 to primary, secondary, and tertiary industries, respectively. Higher values indicate more significant industrial upgrades (Zhang et al., 2023a). Table 9, result (1), shows that upgrading the industrial structure can effectively promote CEP. Result (2) shows that GF is an important moderating variable in industrial structure upgrades that affect the CEP enhancement. Regression result (3) shows that NI is an important moderating variable in industrial structure upgrading to enhance CEP. Regression result (4) shows the regression results of the cross-multiplier terms GF, NI, and industrial structure upgrading, showing that the three cross-multiplier terms are significantly positively related to CEP. Combined with the positive regression results of industrial structure upgrading and CEP in column (1), it can be observed that GF and NI can synergistically promote industrial structure upgrading and then promote CEP. Comparing the significance level and size of the regression coefficients of the IU term in column (1) and the GF × NI × IU term in column (4) showed that the regression coefficients of the cross-multiplier term are large, indicating that the synergistic effect of the construction of GF and NI significantly strengthens the promotion effect of industrial structure upgrading on CEP. These results are consistent with hypotheses 2a and 2b.

4.5.3 Resource allocation

The reallocation of resource factors, such as labor, capital, and technology, can effectively improve the efficiency of resource use and the economic cycle, reduce the production of pollutant emissions, and enhance CEP (Jiang et al., 2020). Zhang et al.

(2019) reported that the optimization of resource allocation (RA) is characterized using the total factor productivity calculated from urban employment and fixed asset investment. Column (1) of Table 10 shows that resource allocation effectively enhanced CEP. Result (2) shows that the GF is an important moderating variable for resource allocation optimization that influences CEP enhancement. Similarly, result (3) shows that NI was a significant moderating variable for resource allocation optimization to enhance CEP. Result (4) is the regression result of the cross-multiplier terms of GF, NI, and RA, which shows that the cross-multiplier terms of the three were significantly positively related to CEP. Combined with the positive regression results of resource allocation optimization and CEP in column (1), it can be observed that GF and NI can synergistically promote the optimization of resource allocation and then promote the improvement of CEP. Comparing the significance level and size of the regression coefficients of the RA term in column (1) and the GF × NI × RA term in column (4) showed that the regression coefficients of the cross-multiplication term were large, indicating that the synergistic effects of GF and NI significantly enhance the promotion of resource allocation optimization on CEP. These results are consistent with hypotheses 1c and 2c.

4.6 Spatial interaction spillover effects of GF, NI, and CEP

In this study, we used the spatial system of simultaneous equation model (3) and investigated the spatial interaction spillover effects among the three using the generalized three-stage least squares (GS3SLS) method, which is used to estimate the overall spatial and considers the spatial correlation and possible correlation between the stochastic perturbation terms of the endogenous variable potential equations, which improves the validity of the estimation results (Rey and Boarnet, 2004).

A spatial correlation test was conducted using the Moran index with a spatial geoeconomic matrix, and the test results confirmed the spatial correlations among GF, NI, and CEP. As shown in Table 11, GF, NI, and CEP had significant spatial interaction spillover effects. The specific results are as follows: regression result (1) shows that local GF and NI can effectively enhance the CEP of local and neighboring cities. However, the effect of both on local CEP was larger than that on neighboring cities. Successful GF programmers and convenient and low-cost NI facilitate the exchange of environmental governance experience and technical cooperation between neighboring cities (Rissman et al., 2020). GF and NI expand the geographical flow boundaries of the factors of production materials, improve the efficiency of resource utilization by market-based financial regulation and remote monitoring, effectively promote the dissemination of green, low-carbon, and environmental protection awareness, and increase CEP through joint regional environmental prevention and control (Zhang et al., 2022d; Zhang et al., 2023a; Zhang et al., 2024). Local CEP is equally effective in enhancing neighboring CEP.

Regression results (2) show that both local CEP and NI can effectively promote the development of local GF and neighboring GF and that the effect of both on local GF is equal to that on neighboring GF. The enhancement of CEP is in line with the concept of green development in China and, thus, can further promote the development of GF, effectively supporting green and low-carbon development. The NI provides information about digital infrastructure support and services for GF development and, therefore, can also effectively promote the development of GF. Forced by the competitive pressure of governmental environmental performance assessments, local governments actively develop GF, which can also promote its development in the surrounding neighboring cities (Zhang et al., 2022a). Simultaneously, the local development of NI and the spread of the digital economy to neighboring cities cause a spillover of green development resources and environmental protection technologies, which can likewise promote the development of GF in neighboring cities. Local GF also significantly promotes GF development in neighboring cities.

Regression result (3) shows that the local CEP can effectively promote local and neighboring NI construction, and the effect on local NI is greater than that on neighboring land. Local GF significantly promotes local NI but inhibits neighboring NI construction. GF provides a large amount of funds for NI construction, but in the case of a limited total amount of funds, more green investment received locally will affect the scale of green funds invested in neighboring areas through the crowding-out effect (Liu et al., 2022a). Benefiting from the benefits of NI, neighboring governments will develop NI vigorously by mimicking a competitive effect (Zhang et al., 2023a). The above findings are also in line with previous research hypothesis H4.

4.7 Discussion

Previous studies have mainly focused on examining the impact of GF and NI on carbon emission separately (Zhang et al., 2022d; Zhang et al., 2023a). With the advent of the digital economy, the development of GF cannot be separated from the support of digital technology, although it can provide for the construction of NI. The construction of the NI provides a hardware foundation for the progress of digital technology, which, in turn, provides technical support for GF development. Therefore, it is important to explore whether there is a superimposed effect on the carbon emission impacts of GF and NI. If this effect exists, what is their common mechanism for effacing carbon emission? Is there a heterogeneous character in regard to the impact of both on carbon emission? However, these questions remain unanswered in previous studies.

Based on existing studies, this study characterized carbon emission levels by CEP and comprehensively measured the levels of GF and NI. Using the panel data fixed effects model, it was found that GF and NI can not only enhance CEP separately but also have a superimposed effect on each other, which further enhances CEP. Green technology innovation, industrial structure upgrading, and resource allocation optimization are common paths for both GF and NI to promote CEP. The impacts of GF and NI on CEP are heterogeneous in terms of the geographic location, level of marketization, policy support for the development of the digital economy, and type of urban development. Further research found that there are also spatial interaction spillover effects among GF, NI and CEP.

Although this study quantitatively analyzed how GF and NI influence CEP and provided novel insights, it is important to acknowledge the inherent limitations of our study. For example, we used a range of approaches to avoid the effects of endogeneity, and the instrumental variable approach to endogeneity testing selected separate instrumental variables for GF and NI. If common instrumental variables of GF and NI can be identified in future research, this will make the conclusion of the synergistic impact of the two more reliable. In addition, this study first used a panel data fixed-effects model and then considered the spatial spillover effect. In future research, we will further discuss the spatial effects of the synergy between GF and NI and include factors such as urban distance. Finally, it is imperative to recognize that the generalizability of our results may be constrained by specific country-level features within the sample. Further research is necessary to evaluate the applicability of these findings in a diverse range of contexts.

Despite these limitations, our study has important implications for promoting low-carbon, green development in Chinese economy. The insights provided are valuable for policymakers and researchers. In addition, this study is of theoretical and demonstrative significance, given that energy transition requires substantial financial and technical support. This not only re-validates the green effect of carbon emission reduction of GF and NI but also demonstrates the synergistic impact between them. This study showed that the GF and NI can promote each other to further deepen their ability to improve CEP. In addition, the study further finds that an improvement in urban CEP has an impact on urban GF and NI, which provides theoretical guidance and policy support for urban green development, financial policy formulation, and NI construction.

5 Conclusion and policy recommendations

5.1 Main conclusion

In this study, the intrinsic relationships among GF, NI, and CEP were investigated using panel data from 285 Chinese cities from 2011 to 2021. The following main conclusions were drawn: (1) GF and NI can not only effectively promote the level of CEP but also synergistically enhance CEP through the superposition effect and mutual reinforcement; (2) heterogeneity analysis shows that GF can effectively promote CEP in all regions of China, high marketization levels, high administrative levels, and resource-based cities, while NI can effectively promote CEP in the east, high marketization levels, high administrative levels, and resource-based cities; (3) green technological innovation, industrial structure upgrading, and resource allocation optimization are important common paths for GF and NI to enhance CEP; (4) local GF can effectively promote local CEP and NI and neighboring CEP and inhibit the surrounding neighboring NI, while NI construction can effectively promote local and neighboring CEP and GF. Simultaneously, CEP can promote local GF and NI and the GF and NI of surrounding neighboring cities. However, the effect of the above objects on the local area is greater than the effect on the surrounding neighboring cities.

5.2 Policy recommendations

The development of GF markets should be continued. We should continue to improve the GF market, establish a sound legal and regulatory system for GF, establish effective incentive mechanisms, and guide financial resources toward green and low-carbon projects. The use of digital and Internet technologies should be promoted to actively innovate carbon finance products.

This further strengthens the construction of new infrastructure, increasing investment in new infrastructure, accelerating the deep integration of new infrastructure with various industries, and fully utilizing policy guidance to ensure the stable development of new infrastructure. We should pay attention to regional development differences, strengthen interregional connections, actively cooperate in infrastructure construction with neighboring regions, and promote the sharing of cross-regional infrastructure equipment and resources.

Continue to deepen cooperation and development between GF and NI, with a focus on regional cooperation and promoting technological innovation, upgrading industrial structure, and optimizing resource allocation of enterprises through the synergy effect between the two. Strengthen the cultivation of consumer awareness of green consumption, promoting green and low-carbon lifestyles.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

HL: writing–original draft and writing–review and editing. ZY: data curation and writing–original draft. JA: data curation and writing–original draft.

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Conflict of interest

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Green financial reporting framework for Paris Agreement parties

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Paris Agreement, green climate funds, financial reporting framework, carbon neutrality, reporting policy gaps, environmental governance, NDCs, COP29

1 Introduction

To tackle the climate change issue, green climate finance is reported as the most crucial component for carbon-neutral development in the developing world (den Elzen et al., 2022; Sattar, 2022). The Paris Agreement (PA) under Article 9 institutionalizes the provision of green financial support to the developing world with these words: "Developed country Parties shall provide financial resources to assist developing country Parties concerning both mitigation and adaptation in continuation of their existing obligations under the Convention" (United Nations, 2015). The developing party countries are encouraged to communicate their green financial needs through their nationally determined contribution (NDC) submissions. The PA under Article 4 states that "Each Party shall prepare, communicate and maintain successive nationally determined contributions that it intends to achieve," and report it to the Convention—United Nations Framework Convention on Climate Change (UNFCCC). To acknowledge, validate, and keep a record of such financial support provided by the developed country parties to the developing world, Article 9 paragraph 7 directs the developed party countries that "Developed country Parties shall provide transparent and consistent information on support for developing country Parties provided and mobilized ... " Similarly, developing countries are directed to provide information on the financial support received. However, the review of NDC submissions from both sides—the developing and the developed party countries—reveals that neither the developing countries have reported their green financial needs in a quantifiable manner nor the developed country parties have provided any note on financial support provided to the developing countries. This has caused a fundamental gap in policymaking and action strategies for achieving carbon-neutral development in the developing world. Hence, academic researchers lack sufficient data on the exact amount of green climate funds developing countries need and receive under the PA (Sattar, 2022; 2023). It requires a consistent structure or a framework for assessing green financial needs in a quantifiable and coherent manner (Mayer, 2023). To justify this gap in the green financial reporting framework and improve the reporting mechanism, we cite some NDC publications randomly accessed from the NDC public registry maintained by the UNFCCC and propose a reporting framework for the green financial needs of developing countries under Article 9 of the PA. COP28 reports to fill this gap with an enhanced transparency framework (UNFCCC, 2023b). The UNFCCC's financial mechanism—Green Climate Fund and Global Environmental Facility—can

play a crucial role to bridge this gap with a unified and specified financial reporting framework.

2 Gaps in green financial reporting

The NDC submissions of some developing countries like Albania, Armenia, Azerbaijan, Brazil, Dominica, Georgia, Jamaica, Kazakhstan, Macedonia, Maldives, Serbia, Thailand, Tonga, and Tuvalu report no quantifiable information on green financial needs under Article 9 of the PA. Some other developing countries provide general information on green financial needs such as Belize $1.71 billion (NDC., p. 33), Fiji $2.97 billion (NDC., p. 15), Mauritius $4.5 billion (NDC., p. 30), Palau $5.5 million (NDC., p. 5), and Suriname $696 million (NDC., p. 27). However, they did not clarify whether this amount is required for climate change mitigation or adaptation actions. Hence, this cost is reported for their conditional or unconditional targets. Only a few countries have partly provided categorical information on green financial needs for conditional and unconditional targets. For instance, Indonesia reports $285 billion (NDC., p. 19) for conditional mitigation targets and $281 billion (NDC., p. 19) for unconditional mitigation targets. Saint Lucia reports $368 million (NDC., p. 2) for conditional mitigation targets but no information on unconditional mitigation targets. However, none of them provided complete information on their green financial needs both for mitigation and adaptation targets categorically, except Namibia, which seeks a $5.33 billion total cost, including $3.25 billion for conditional mitigation targets, $0.36 billion for unconditional mitigation targets, $1.55 billion for conditional adaptation, and $0.17 billion for unconditional adaptation (NDC., p. 2). On the other hand, developed party countries provide no information on green financial support provided to developing party countries. It confirms a fundamental gap in green financial reporting mechanisms and requires a clear reporting framework for more transparent and coherent data to improve the implementability of NDCs (Pauw and Klein, 2020). Röser et al. (2020) validated it by noting that "More analytical, financial, and technical resources are needed to implement the first round of NDCs and support countries in preparing future NDC cycles (p. 415)." COP members and climate science experts report political institutions as the leading force to implement such frameworks (AL-Abrrow et al., 2018; Adloff and Neckel, 2019; Victor et al., 2022).

2.1 Gaps in the policy framework

The PA under Article 4 paragraph 2 states that "Each Party shall prepare, communicate, and maintain successive nationally determined contributions that it intends to achieve. Parties shall pursue domestic mitigation measures, with the aim of achieving the objectives of such contributions." The point of focus is that it lacks a clear direction for reporting green financial needs in a quantifiable manner. It does not provide further specifications on green financial reporting. For instance, how much funds do the developing party countries need to achieve their conditional and unconditional mitigation targets? Similarly, how much finance do they need for their conditional and unconditional adaptation targets? Most of the NDC targets by the developing party countries are conditional on external support (Mills-Novoa and Liverman, 2019; Pauw et al., 2020; Ali et al., 2022; Shah et al., 2022; Latif et al., 2023; Xu et al., 2023). It is, therefore, crucial to have a consistent reporting framework. Some developing countries have reported this framework gap in their NDC submissions. For instance, Egypt (NDC., p. 28) reports that the "MRV [monitoring, reporting, and verification] system should be institutionalized." A recent study notes that "Changes in capacity additions and capital investments, such as those presented in this study, could be further challenged by the need for rapid mobilization of capital, investments in infrastructure, setting up of the supporting institutional and regulatory frameworks . . . " (Iyer et al., 2017). In our opinion, this gap can be filled by providing the developing party countries with a consistent reporting framework for charting their green financial needs in a categorical and quantifiable manner. Here, in Table 1, we propose a template for charting such needs. The developing party countries can use it for reporting their green financial needs in their future NDC submissions. It will improve the green financial reporting mechanism under Article 9 of the PA and work as a "progress tracker" function suggested as one of the most important components for the implementation of NDCs (Jernnäs, 2023). The upcoming Conference of the Parties (COP29) can potentially consider it for institutionalization. It can also help the next COP for charting cross-country financial needs in a consistent manner decided (Decision -/CP.28 -/CMA.5) in COP28 with these words: "Decide that arrangements with the Fund, consistent with the Governing Instrument of the Fund and to ensure that the Fund is accountable to and functions under the guidance of the Conference of the Parties and the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement, are to be approved by the Conference of the Parties at its twenty-ninth session (November 2024) and the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement at its sixth session (November 2024); " (UNFCCC, 2023a).

3 Discussion

A consistent reporting mechanism for green financial reporting under Article 9 is crucial for policymakers, practitioners, and academic researchers. Why most developing countries are unable to report their green financial needs might be because of their inability to estimate support needs. The estimation of green financial needs is challenging for some countries, which require financial and technical capacities for research and collecting data. For instance, Indonesia (NDC., p. 19) states that "Constraints has [have] also been faced in estimating support needs, in particular to the methodological approach used to assess finance needs for mitigation and adaptation, data availability and reliability, and diverse perceptions of stakeholders on NDC financing." Egypt (NDC., p. 28) reports that "The national climate reporting relies mainly on donor-funded projects and contracting consultants on an *ad hoc* basis to prepare the reports required under the UNFCCC." In addition, it states that "Building a strong foundation for the

TABLE 1 Proposed financial reporting framework under Article 9 of the PA.

Country	Total cost	Mitigation cost for		Adaptation cost for	
		Conditional targets	Unconditional targets	Conditional targets	Unconditional targets
1	---	---	---	---	---
2	---	---	---	---	---
3	---	---	---	---	---

planning, implementation, and reporting of national climate actions requires adequate institutional, technical, and financial arrangements." Likewise, Zimbabwe (NDC., p. 34) mentions that "There is a need for an efficient system to assess financial support needs and for tracking financial support received." It shows the nucleus of the reporting problem is neither from the developing country parties nor the developed one. It is a strategic issue. We noted that it is too early to ask developing countries to report their green financial needs as financial and technical assistance comes as a prerequisite for green financial reporting. On the other hand, the developed party countries might not be able to report transparent information on support under Article 9 paragraph 7 about the provision of green climate funds to the developing party countries due to the missing prerequisite information on green financial needs from the developing party countries. In our opinion, the financial reporting chart proposed in Table 1 can facilitate both sides for green financial reporting under the PA. The upcoming COP29 can potentially consider it as a policy frame for green financial reporting under Article 9 of the PA. The implementation can be facilitated by engaging the subsidiary bodies of UNFCCC's financial mechanism with nationally designated entities (NDEs) of all party countries.

Author contributions

US: conceptualization, formal analysis, investigation, methodology, supervision, validation, writing–original draft, and writing–review and editing. RL: investigation, methodology, validation, and writing–review and editing. YW: data curation, investigation, project administration, and writing–review and editing. AS: data curation, investigation, validation, and writing–review and editing.

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Conflict of interest

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The impact of green finance on the intensity and efficiency of carbon emissions: the moderating effect of the digital economy

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Carbon emissions have become a global challenge that threatens human development. Governments have taken various measures to reduce carbon emissions, and green finance is an important and innovative way to realize carbon emission reductions. This paper uses data on a prefecture-level city in China to explore the impact of green finance on carbon emission intensity from both theoretical and empirical perspectives, and analyzes the mechanisms by which green finance affects carbon emission intensity. On this basis, this paper further analyzes the impact of green finance on carbon emission efficiency. In addition, this paper introduces variables related to the digital economy to perform a comprehensive examination of the moderating effect of digital economy development on the relationship between green finance and both carbon emission intensity and efficiency. The results indicate that green finance reduces carbon emission intensity and that green innovation, green total factor productivity and the transformation and upgrading of industry are important mediating mechanisms. Meanwhile, analysis shows that green finance improves carbon emission efficiency. This paper also finds that the digital economy significantly enhances the role of green finance in reducing carbon emission intensity and promoting carbon emission efficiency, and makes a positive contribution to promoting carbon emission reduction. The findings will contribute to strengthening the government's capacity for environmental protection, developing green finance, and reducing carbon emissions.

KEYWORDS

green finance, carbon emission intensity, carbon emission efficiency, digital economy, China

1 Introduction

Climate change is a major and urgent global challenge for humanity. Anthropogenic carbon emissions that seriously threaten sustainable development worldwide (Glasnovic et al., 2016; Yang et al., 2021) and are of great global concern (Rezanezhad et al., 2020; Pan et al., 2022a). Realizing carbon emission reduction cannot only rely on the regulation of the market, but also requires the government to formulate effective environmental policies for regulation. Green finance is one of the important policy tools. As a way to promote sustainable development, green finance has been developing rapidly and is attracting increasing attention globally (Bai and Lin, 2024), and is recognized as an effective tool to reduce carbon emissions.

Green finance aims to facilitate the development of green projects by providing financial services such as investment, financing, and funding (Ji and Zhang, 2019). The term "green finance" covers green credit, green bonds, green funds, green insurance, green investment, and other financial instruments with green characteristics. Green finance has the dual functions of financial resource allocation and environmental regulation (Tolliver et al., 2021), and is widely recognized as the key to combating climate change (IFC, 2016). Therefore, green finance may be an important way to reduce carbon emissions and achieve both the Paris Agreement and the United Nations Sustainable Development Goals (Umar et al., 2023). In this context, this paper attempts to explore the impact of green finance on carbon emission intensity and the intrinsic mechanism by which this influence occurs, and further to analyze the impact of green finance on carbon emission efficiency.

In addition, the rapid development of the digital economy has led scholars and policymakers to consider its role in environmental protection and sustainable development. As a new economic form, the digital economy takes data resources as the key production factor, relies on digital technology innovation as the core driving force, and continuously improves the digitization, networking, and intelligence of the society through the mode of digital industrialization and industrial digitization. This can provide technical support for green development (Balcerzak and Pietrzak, 2017; Yi, Liu, Sheng, Wen, 2022), and produce certain beneficial environmental effects while effectively promoting high-quality economic development. At the same time, the advantages of the digital economy–in terms of efficient information dissemination, data creation and sharing–can enhance the production and operation efficiency of enterprises, thus reducing energy consumption and carbon emissions (Koch and Windsperger, 2017). The digital economy also empowers the traditional financial sector to improve the efficiency with which green finance is implemented, optimize resource allocation by green finance, and strengthen the environmental regulation function of green finance. Thus, another central question of this research concerns the impact of the digital economy on the relationship between green finance and carbon emissions.

China, the world's second largest economy, has become the world's largest emitter of carbon dioxide (CO_2), which has a significant impact on global climate change and poses a threat to China's own sustainable development (Shao et al., 2019; Ibrahim and Ajide, 2021; Jia et al., 2022). In 2020, China accounted for 30.7% of global CO2 emissions, a greater share than that of the United States (13.8%) or Europe (11.1%) (Statistical Review of World Energy, 2021). To reduce carbon emissions, the Chinese government has set the solemn goal of achieving carbon neutrality by 2060 (Lin and Ma, 2022). Exploring feasible carbon reduction measures can not only solve the serious greenhouse effect problem and realize the above commitment, but also provide Chinese solutions for other countries to achieve carbon reduction and promote green development. Meanwhile, China's digital economy is developing rapidly: it reached a size of 39.2 trillion yuan in 2020, accounting for 38.6% of China's GDP (Zhang et al., 2022). These facts motivated our analysis of the core issues of this paper in the context of China.

We use prefecture-level data to comprehensively measure the degree of green finance development, carbon emission intensity and efficiency, and the digital economy index in China based on a constructed measurement system. Using the results, the impact of green finance on carbon emission intensity and efficiency is empirically examined. Meanwhile, we select three indicators, namely, green innovation, green total factor productivity and the upgrading of industrial structure, to examine the mediating mechanisms through which green finance affects carbon emission reduction. Further, we explore the moderating effect of digital economy on the relationship between green finance and carbon emission intensity and efficiency.

The contribution of this paper is threefold. First, we analyze the role green finance plays in carbon emission intensity and efficiency. The extant literature mostly examines important factors for carbon emission reduction from the perspectives of environmental regulation, green innovation, urbanization, and industrial development, but less so from the perspective of green finance. In addition, extant studies on carbon emissions focus on the intensity or total amount of carbon emissions, while ignoring the efficiency of carbon emissions. This paper not only analyzes the impact of green finance on carbon emission intensity, but also further examines the impact of green finance on carbon emission efficiency using a variety of measurement methods.

Secondly, unlike extant research which uses green credit, green investment, green funds or other single indicators to measure green finance, we utilize a variety of indicators to construct the measurement system of green finance, which can comprehensively evaluate the degree of green financial development and enhance the accuracy of the study.

Thirdly, we introduce the digital economy, a new and rapidly developing economic model, and measure the digital economy development index of prefecture-level cities on the basis of multiple indicators. We then link the digital economy, green finance, and carbon emissions to explore the moderating effect of the digital economy on the relationship between green finance and carbon emission intensity and efficiency. This broadens research on the effect of the digital economy on carbon emission reduction.

The paper is organized as follows. The second section presents our theoretical analysis and hypotheses; the third section details the empirical design employed in the study; the fourth section contains an analysis of the results; the fifth section presents further analysis; the sixth section analyzes the moderating effect of the digital economy; and the final section draws conclusions from the study.

2 Literature review

2.1 Green finance and carbon emissions

Carbon dioxide (CO2) emissions are an important contributor to global warming and a major environmental challenge that mankind is currently facing (Koengkane et al., 2019). Many studies have examined ways to reduce the intensity of carbon emissions. Estrada and Santabarbara (2021) argued that through the imposition of carbon tax, an environmental tax reform, technological innovation and clean energy use can be promoted, thus reducing the amount of carbon emissions; Chen and Lin (2021)

found that carbon emissions trading is also an important market mechanism to promote carbon emission reduction and realize low-carbon economic development. In addition, some studies have analyzed carbon emission efficiency. Lin et al. (2017) used the Shephard input distance function and the nonparametric common Frontier method to construct a carbon emission performance index to assess the carbon emission efficiency of energy-intensive industries in China.

Among the many studies on carbon emission reduction, the role played by finance has received attention from scholars. Jeucken (2001) studied the relationship between financial institutions and sustainable development, and points out that reducing carbon emissions requires attention to the key role of banks. Altaghlibi et al. (2022) argued that banks and financial regulators can promote green finance through the regulation of money, credit, and financial systems to guide the flow of capital to low-carbon sectors, thus promoting a low-carbon transition. Based on these studies, some scholars have examined the relationship between finance and the environment. Koengkan et al. (2018) examined the impact of national financial openness on environmental degradation and found that financial openness increased carbon emissions in both the short and long term; Koengkan et al. (2020) found that financial openness, economic growth, and primary energy consumption increased environmental degradation in both the short and long term after conducting a study using data from Latin American and Caribbean countries.

Some scholars further analyze the relationship between green finance and carbon emissions. Studies have used different dimensions of data to conduct empirical tests, and most of them found that a certain type of green finance can effectively reduce the intensity of carbon emissions. Wan et al. (2022) examined the relationship between green real estate financing and carbon dioxide emissions from the construction sector in 100 developed and emerging countries, and found that there is a negative correlation between the two, and that this relationship is particularly obvious in emerging countries. In addition, the carbon emission reduction effects of green bonds, green credit, and green venture capital have also been confirmed by the study. Mamun et al. (2022) found that green bonds can promote global economic decarbonization; Hu and Zheng (2022) and Wang et al. (2021b) showed that green financial instruments such as green credit and green venture capital can all reduce carbon emission intensity; Qin and Cao (2022) used the Green Credit Guidelines as a green financial policy and constructed a difference-in-differences model, and found that green finance represented by green credit can significantly reduce the carbon emissions of highly polluting enterprises.

Meanwhile, some studies construct the measurement system of green finance and use a variety of indicators to measure green finance, and then use the measurement results to analyze the impact of green finance on carbon emissions. Pretis et al. (2017) combined the time series test of different countries and found that green finance plays a positive role in carbon emission reduction; Khan et al. (2019) analyzed the data of the BRICS countries and found that the development of green finance can inhibit carbon dioxide emissions; Chen and Chen (2021) used a spatial dynamic panel model and found that green finance can promote carbon emission reduction in the region. Chen and Chen (2021) use a spatial dynamic panel model and find that green finance can promote carbon reduction and emission reduction in the region, and inhibit carbon emissions in neighboring regions; Guo et al. (2022) test the impact of green finance on agricultural carbon emissions based on the perspective of meso-industry, and the study shows that green finance can effectively reduce carbon emissions in the agricultural sector.

2.2 Digital economy and carbon emissions

The concept of digital economy was first proposed by Tapscott (1994), who described digital economy as an emerging form of economy that expresses information technology and communication economy, production, and lifestyle. Existing studies have mainly used the entropy weight method, principal component analysis, and input-output method to measure the degree of development of the digital economy. Peng and Dan (2023) chose the three indicators of the Internet, mobile telephony, and digital inclusion, and used the entropy weight method to measure the digital economy. Ma et al. (2022b) constructed a digital economy measurement system using principal component analysis, and measured China's digital economy development index by utilizing the development of telecommunication industry, Internet industry, computer service industry and software industry on China's digital economy.

Research on the digital economy has focused on urban development (Zhu and Chen, 2022), corporate innovation (Luo et al., 2023), income distribution (Peng and Dan, 2023), fintech (Chen et al., 2022), and total factor productivity (Pan et al., 2022b). Yang et al. (2023a) found that the digital economy plays an important role in promoting industrial green transformation, and that the evolution of the digital economy is strongly correlated with industrial green transformation in space and time. 2023) found that the digital economy plays an important role in promoting the green transformation of industries, and that the evolution of the digital economy has a strong spatial and temporal correlation with the green transformation of industries. Ren et al. (2023) confirmed that the technology and efficiency revolution triggered by the digital economy will upgrade the existing production processes across the chain and accelerate the transformation. Chen et al. (2022) argued that the digital economy promotes fintech through technological advancement and credit asset quality.

Unlike the traditional economy, the digital economy, as a new key driver of the economy and society (Cong et al., 2021), has given rise to new economic forms and driven profound changes in the mode of production and governance, leading to lower resource consumption and less environmental pollution (Murthy et al., 2021). Xiao et al. (2023) empirically examined the direct, indirect, spatial spillover and non-linear effects of the digital economy on green development using data from 284 prefecture-level cities in China, and all found that the digital economy significantly promoted green development; Ma and Zhu (2022) proposed that the green financial system can accelerate the green transformation of traditional manufacturing industry, improve the technological maturity of manufacturing industry, and reduce environmental problems.

In addition, some studies have directly analyzed the relationship between digital economy and carbon emissions. Chen et al. (2023)

analyzed the impact of digital economy on carbon emissions by constructing a two-way fixed-effects model using provincial panel data in China, and found that the development of digital economy significantly reduces the intensity of carbon emissions, and that government support positively moderates the relationship between digital economy and carbon emissions. Wang and Li (2023) concluded that the development of digital economy significantly reduces carbon emissions, and this effect has economic dimension heterogeneity, industrial heterogeneity, production and life heterogeneity, and urban-rural heterogeneity. Yi et al. (2022) constructed a spatial panel Durbin model and a mediation effect model to study the mechanism and impact of digital economy on carbon emission reduction. The results showed that the development of digital economy has a significant spatial spillover effect on carbon emission reduction, which means that carbon emission reduction can be indirectly affected by the digital economy through the transformation of energy structure.

2.3 Research gap

Although existing studies have examined the paths affecting carbon emissions from different aspects, they have mostly analyzed them from the aspects of fiscal policy, tax policy, environmental regulation, and there are fewer studies that have constructed green finance indicators from multiple perspectives and analyzed the relationship between green finance and carbon emissions. At the same time, these studies have not reached a unified conclusion. In addition, the existing studies have only analyzed the impact of these factors on carbon emission intensity, and fewer studies have further examined the impact on carbon emission efficiency. Furthermore, the digital economy is a new type of economic development, which has an impact on the environment, society, and economy. However, existing studies have less systematically measured the degree of digital economy development, and less examined the carbon emission reduction effect of digital economy. Therefore, this paper systematically constructs the measurement system of the carbon emission intensity, carbon emission efficiency, green finance, and digital economy to measure these variables. On this basis, this paper further combines green finance, digital economy, and carbon emission intensity, and examines the impact of green finance on carbon emission reduction, and further examines the moderating effect of digital economy on the relationship between the two. This paper enriches the existing research on the realization path of carbon emission reduction, the environmental effect of green finance and the carbon emission reduction effect of digital economy, thus making up for the shortcomings of the existing research.

3 Theoretical analysis and hypothesis

3.1 The impact of green finance on carbon emission intensity

Due to the non-competitive and non-exclusive nature of air resources, carbon emissions have strong negative externalities, which makes it difficult to clearly define their property rights and therefore leads to market failure. At this point, it is difficult to rely solely on the market to achieve Pareto optimality of carbon emissions, as market players will not spontaneously internalize the social costs that are higher than the private costs, and market decisions in the equilibrium state will bring unnecessary losses. Therefore, as the "visible hand," the government should intervene in the carbon emission market to realize the optimal allocation of resources. There are many government policies to intervene in the carbon market, and green finance is an important market-incentivized environmental policy tool. Green finance refers to the fact that financial institutions take into consideration the environmental behavior of market players when making decisions, and through a series of institutional arrangements, allocate more financial resources to environmentally friendly market players, industries, and products, reflecting the green preference of financial decision-making (Freebairn, 2012; Huang et al., 2022).

With the dual characteristics of environmental regulation and financial allocation (Lu et al., 2021), green finance can inhibit the access to capital of high-carbon emitting enterprises, rationally allocate financial resources to green industries and green projects, and utilize financial leverage to achieve climate goals, which is widely considered an effective policy tool to promote carbon emission reduction and green development (Freebairn, 2012; Jin et al., 2022). Specifically, green finance provides market players with differentiated and preferred financial products and services based on their environmental behavior. At the same time, it relies on the resource allocation function of the financial market to establish an incentive and constraint mechanism, which influences the production and operation activities of market players, and thus has an impact on the intensity of carbon dioxide emissions (Jalil and Feridun, 2011; Khan et al., 2018). For example, green finance sets higher lending rates and reduces the amount of credit up to for high-pollution and high-emission enterprises, which limits the financing of these enterprises and incentivizes them to shift towards low-carbon and cleaner production and operation models, thus reducing the carbon emission intensity. On the contrary, for environmentally friendly enterprises, green finance has incentivized them to operate continuously by lowering the lending rates and financing thresholds, promoting their sustainable development, and further reducing the carbon emission intensity, thus realizing a virtuous cycle of enterprise development and carbon emission reduction (Wang and Wang, 2021; Mirza et al., 2023). Therefore, Hypothesis 1 of this paper is proposed.

H1: *Green finance reduces carbon emission intensity.*

Green technology innovation has the disadvantages of large investment amount, long investment cycle and high investment risk, and enterprises face greater difficulties in carrying out green innovation (Hall, 2002). Therefore, it is necessary for the government to give certain incentives to promote the green innovation of enterprises. Green finance can guide the flow of financial resources to green innovation activities through resource allocation, which reduces the risk of innovation and research and development of enterprises, thus promoting green innovation (Haas and Popov, 2019; Wang and Yang, 2020). On the one hand, green finance can provide financial support for green innovation. External financing from financial institutions is an important source of funds for enterprises to carry out green innovation activities (Su et al.,

2022). Green finance provides lower loan interest rates and financing thresholds for enterprises' green innovation activities, which encourages enterprises' green innovation and thus promotes their green technological innovation (Zhao et al., 2023). In addition, green finance can effectively solve the problems of large initial investment, long profit cycle, and unpredictable risk of green innovation funds, and alleviate the financial constraints of enterprises at the initial stage of green innovation (Du et al., 2022).

On the other hand, green finance incentivizes high-energy consumption and high-emission enterprises to reduce their reliance on high-pollution production experience patterns, prompting them to change to an environmentally friendly production mode, thereby promoting green innovation (Berrone et al., 2013). Due to industry constraints, high-polluting and high-emission firms are forced to transform their original crude production methods, which requires the support of green technological innovation. Therefore, green financial instruments can also promote heavy polluting enterprises to reduce carbon emissions through technological innovation (Bruce, 2014; Hong et al., 2021). Some studies have showed that green finance can promote green innovation. For example, Han et al. (2022) found that green finance can promote green innovation in heavy polluters. Wang et al. (2023a) employed China's 2017 green finance reform pilot as a quasi-natural experiment, and found that the green finance pilot promotes green innovation. Based on the above analysis, Hypothesis 1a is proposed.

H1a: *Green finance promotes green innovation, thereby reducing carbon emission intensity.*

Total factor productivity (TFP) is the increase in output due to technological progress in addition to labor and capital inputs. Endogenous growth theory considers it to be the driving force for achieving sustainable economic growth. Unlike TFP, green total factor productivity (GTFP) is TFP under environmental constraints, which considers the negative externalities of environmental regulations (Chung et al., 1997). GTFP utilizes inputs, outputs, and undesired outputs to test economic growth (Li et al., 2022a; Liu et al., 2022). The development of green finance can reduce energy consumption on the input side and excessive environmental hazards on the output side, improve energy efficiency, and thus enhance GTFP (Li et al., 2022b). Meanwhile, green finance can improve the GTFP of enterprises, realize high-quality development of the economy, and promote green economic development. It improves environmental performance while increasing productivity, thus increasing GTFP (Xia and Xu, 2020; Yan et al., 2020). Some studies have also confirmed that green finance contributes to GTFP (Liu et al., 2021; Meo and Abd Karim, 2021). Based on this, Hypothesis 1 b is proposed.

H1b: *Green finance enhances GTFP, thereby reducing carbon emission intensity.*

Green finance is characterized by capital orientation and industrial integration. It guides the flow of capital from backward industries to green industries, restricts the financing of polluting industries, and encourages the upgrading of crude traditional industries, thus realizing industrial transformation (Bai and Lin, 2024). Specifically, green finance guides the transfer of financial resources from high-pollution and high-emission industries to green and low-carbon industries and environmentally friendly industries, and guides the direction of industrial development with the flow of funds, which realizes the transformation of industrial structure, optimizes the industrial structure, and then reduces the intensity of carbon emissions (Wang and Wang, 2023). At the same time, green finance guides enterprises to realize resource reconfiguration under the guidance of the green development concept and gradually forms an industrial structure with green industry as the core, promoting the adjustment of industrial structure within enterprises (Song et al., 2021; Zhang et al., 2021). Under the constraints of green financial development, high-pollution and high-emission industries face greater survival pressure, which hinders the development of these industries. To seek their own sustainable development, these enterprises will endogenously carry out industrial transformation and choose to transform into environmentally friendly tertiary industries (Wang et al., 2021a). In addition, the green finance policy, as a signal for the government to promote green development and phase out high-pollution and high-energy-consumption industries, plays a warning role for high-pollution and high-energy-consumption industries. The green finance policy guides private capital to flow spontaneously to green projects and activities (Zhang et al., 2021). These enterprises actively realize the green transformation of production and operation as well as industrial structure, eliminate backward production capacity, and build a green production system through external regulation and their own actions. Therefore, Hypothesis H1c is proposed.

H1c: *Green finance promotes industrial transformation and upgrading, thereby reducing carbon emission intensity.*

3.2 The impact of green finance on carbon emission efficiency

Carbon emission efficiency is the maximum desired output and the minimum carbon emissions that can be achieved when input factors such as capital, labor and energy are certain. Carbon emission efficiency, as a key indicator of green and low-carbon development, accurately utilizes the input-output relationship to reflect the relationship between economic growth and carbon emissions. Therefore, any behavior that can reduce carbon emissions without reducing economic output or in-crease economic output without increasing carbon emissions can improve carbon emission efficiency. The theoretical analysis in the previous section shows that green finance can reduce carbon emission intensity through the tendentious allocation of resources. Similarly, green finance can achieve carbon emission efficiency by strategically allocating financial resources and incentivizing market players to use the least amount of energy to achieve the greatest economic output (Sohail et al., 2022; Tian et al., 2022). For example, green finance can promote green innovation, which reduces the amount of energy consumption required to reduce the unit output of enterprises, improves the efficiency of energy use of enterprises, and thus reduces the carbon emissions. Some studies have also demonstrated the positive effect of technological progress on improving carbon emission efficiency (Fan et al., 2021). Green finance can also facilitate the transformation of industries and

energy infrastructure, promote the op-timization of energy structure and upgrade of industrial structure, and thus improve carbon efficiency (Wang and Wang, 2021; Sun and Chen, 2022). In addition, green finance's preference for environmentally friendly enterprises incentivizes them to take effective measures to improve carbon efficiency (Zhang et al., 2022). Based on the above analysis, Hypothesis 2 is proposed.

H2: *Green finance improves carbon efficiency.*

3.3 Moderating effects of the digital economy on the relationship between green finance and carbon emissions

Digital economy is a new economic model that takes big data as its support, the Internet as its platform, and artificial intelligence as its main mode of operation. Its rapid development can improve the allocation efficiency of green financial resources, and better develop the role of green finance in reducing carbon emission intensity and improving carbon emission efficiency (Lange et al., 2020; Liu et al., 2021). Specifically, the digital economy plays a role in regulating the relationship between green finance and carbon emissions in three ways.

First, the digital economy applies digital technologies such as big data, cloud computing, and artificial intelligence to the production and operation of enterprises, which can not only promote the transformation and upgrading of enterprise production technology and organizational form, improve the output efficiency of enterprise production, reduce the dependence on energy in the production process, and realize the efficient use of energy and resources (Dong et al., 2022; Yi et al., 2022), but also lead to the reform of the internal management of the enterprise, reduce the cost of operation, and alleviate the financing constraints of green technology development and reduce green production costs. As a result, enterprises can reduce unnecessary carbon emissions, so that green finance can better play a positive role in reducing carbon emission intensity and enhancing carbon emission efficiency (Koch and Windsperger, 2017; Hao and Wu, 2021).

Second, the advanced digital technology and massive data elements spawned by the development of the digital economy can apply technologies such as big data, artificial intelligence and distributed management to the production and operation of market entities, which is conducive to the integration of fragmented corporate information and the promotion of low-carbon technological innovation as well as cleaner energy production (Marcel and Stefanie, 2020). At the same time, digital technology links green finance, carbon foot printing and carbon sink systems and visualization, which can provide all-round and multidimensional supervision and detection of production enterprises. This can also accurately calculate the carbon intensity and efficiency of enterprises and incentivize them to reduce carbon emissions (Ding et al., 2022), thus deepening the relationship between green finance and carbon intensity and efficiency.

Finally, the development of digital technology has enhanced the effectiveness and availability of corporate carbon information, allowing resources to be better matched through the market. The continuous integration of the digital economy and the real economy can realize the effective use of resources and better promote green and low-carbon development (Ren et al., 2021; Zhang et al., 2022). In addition, the development of digital economy accelerates the development of digital finance, which, combined with green finance, give rise to the new product of green digital finance, thus strengthening the relationship between green finance and carbon emissions. Based on the above analysis, Hypotheses 3a and 3 b of this paper are proposed.

H3a: *The development of digital economy strengthens the role of green finance in reducing carbon emission intensity.*

H3b: *The development of digital economy strengthens the role of green finance in promoting carbon emission efficiency.*

4 Empirical design

4.1 Model

4.1.1 Model construction

We construct the following Models (1) and (2) to identify the impact of green finance on carbon emission intensity and carbon emission efficiency respectively. Following Yang et al. (2023b) and Ran et al. (2023), we construct two-way fixed effects for empirical testing. The two-way fixed effects model can control for individual effects and time fixed effects while dealing with heteroskedasticity and autocorrelation in panel data, thus improving the accuracy of the estimation results (Guo et al., 2022).

$$CarInten_{it} = \alpha_0 + \alpha_1 Green_{it} + \gamma \boldsymbol{X}_{it} + \gamma_i + \delta_t + \varepsilon_{it} \quad (1)$$

$$CarEff_{it} = \theta_0 + \theta_1 Green_{it} + \gamma \boldsymbol{X}_{it} + \gamma_i + \delta_t + \varepsilon_{it} \quad (2)$$

where i and t are prefecture-level city and year, respectively; $CarInten$ is the carbon emission intensity; $CarEff$ is the carbon emission efficiency; $Green$ is the level of green finance; $Control$ is a series of time-varying control variables; γ_i and δ_t denote the city fixed effect and year fixed effect, respectively. Year fixed effects are introduced to control for factors that do not vary with individuals at the year level, while city fixed effects are introduced to control for factors that do not vary with individuals at the city level; and ε_{it} is the error term. Standard deviations are clustered at the prefecture level. Models (1) and (2) are both two-way fixed effects models. The regression coefficients we focus on are α_1 and θ_1, which represent the impact of green finance on carbon emission intensity and carbon emission efficiency, respectively. If α_1 is significantly negative, it indicates that the increase in the level of green finance reduces carbon emission intensity; if θ_1 is significantly positive, it indicates that the increase in the level of green finance improves carbon emission efficiency. The empirical method framework is shown in Figure 1. The empirical analysis steps are shown in Figure 2.

4.1.2 Variable definition and explanation

We study the impact of green finance on carbon emissions and examine the moderating role of the digital economy in it. Therefore, the dependent variable is carbon emission, the core independent variable is green finance, and the moderating variable is digital economy.

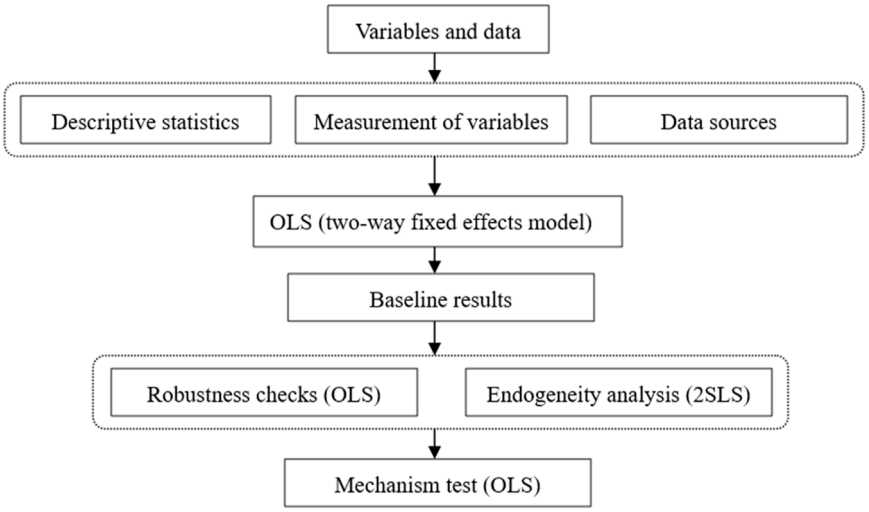


FIGURE 1
The method framework of this study.

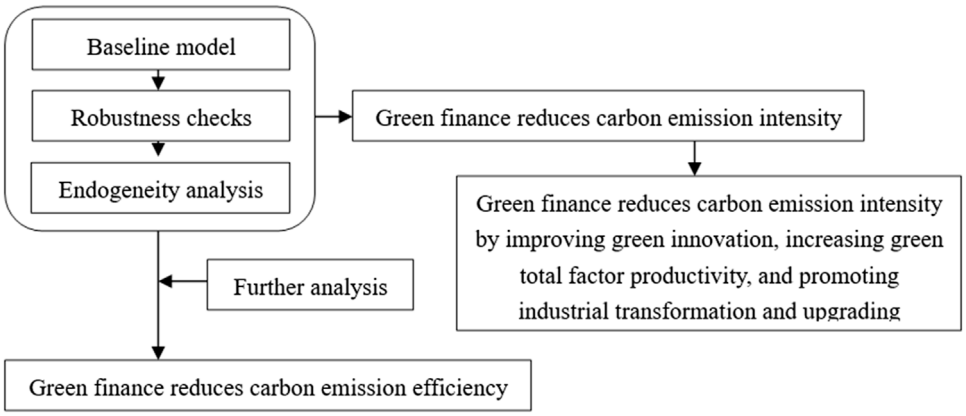


FIGURE 2
The findings of this study.

4.1.2.1 Dependent variable

The dependent variables are carbon emission intensity (*CarInten*) and carbon emission efficiency (*CarEff*). For the carbon emission intensity variable, we use the sum of the three scopes of carbon emissions to measure the total carbon emissions at the prefecture-level city. Specifically, carbon emissions include three main aspects: first, all direct emissions within the urban jurisdiction, including those from transportation and buildings, industrial processes, agriculture, forestry and land-use change, and waste disposal activities; second, indirect energy-related emissions that occur outside the city's jurisdiction, including emissions generated for electricity, heating and/or cooling; third, other indirect emissions caused by activities within the city that occur outside the jurisdiction but are not included in the second category, including emissions from the production, transportation, use and waste disposal of all goods purchased from outside the jurisdiction.

In terms of direct or indirect emissions, scope 1 includes all direct emissions within the city's jurisdiction; scope 2 refers to energy-related indirect emissions that occur outside the city's jurisdiction; and scope 3 refers to other indirect emissions caused by activities within the city that occur outside the jurisdiction but are not covered by scope 2.

In addition, we use the alternative measure of carbon emissions intensity for the robustness test. Following Shan et al. (2018), we use energy supply statistics to calculate carbon dioxide emissions from fossil fuel combustion (crude coal, crude oil, and natural gas). This is done by multiplying the apparent consumption of the fuel by the corresponding carbon conversion factor and subtracting the use and loss portion of the apparent consumption of non-energy fuels, thus yielding the total carbon emissions.

In terms of the carbon emission efficiency variable, following Tone (2011), we use both the SBM model and the Non-Radial

TABLE 1 Indicators for the construction of the Green Finance Index.

Indicator	Measure
Green Investment	Investment in environmental pollution control/GDP
Green Insurance	Environmental pollution liability insurance income/total premium income
Green Credit	Credit volume for environmental protection projects/total credit volume
Green Bonds	Total green bond issuance/total of all bond issuance
Green Support	Fiscal environmental protection expenditure/fiscal general budget expenditure
Green Fund	Total market value of green funds/total market value of all funds
Green Equity	Carbon trading, energy use right trading, emission right trading/total equity market transactions

Directional Distance Function (NDDF) to measure. Among them, the input variables include capital stock, total urban unit employees, and energy consumption; the output variables include GDP; and the non-expected outputs are carbon emissions, involving coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, and natural gas. The process of calculating non-expected outputs is based on the measurement methodology of the IPCC Guidelines for National Greenhouse Gas Emission Inventories, 2006 edition (IPCC, 2006).

4.1.2.2 Key independent variable

The key independent variable is green finance (*Green*). The green finance index data of each prefecture-level city is measured by the entropy method. Entropy method is a mathematical method used to determine the degree of dispersion of an index. The greater the degree of dispersion, the greater the influence of the index on the comprehensive evaluation. Indicators for the construction of the Green Finance Index are shown in Table 1.

4.1.2.3 Moderating variable

The moderating variable is digital economy (*Digital*). The number of Internet broadband access users per 100 people, the proportion of employees in computer services and software industry in urban units, the total amount of telecommunication services *per capita*, the number of cell phone subscribers per 100 people, and the digital financial inclusion index are selected, and the entropy weighting method is used to obtain the composite index value. The entropy method is a mathematical method used to determine the degree of dispersion of an indicator. The greater the degree of dispersion, the greater the impact of the indicator on the overall evaluation. The entropy value can be used to determine the degree of dispersion of an indicator. We use the entropy weight method to measure the development of the digital economy through Stata 17.0, including six steps. Step 1: data standardization; Step 2: calculate the weight of each indicator; Step 3: calculate the entropy value; Step 4: calculate the value of the utility of information; Step 5: calculate the weight of each indicator; Step 6: calculate the samples to derive a comprehensive score. These six steps are all operated in stata17.0, involving the commands of global, qui su, gen, replace, egen, rowtotal, drop.

4.1.2.4 Mechanism variables

Mechanism variables include green innovation level (Innovation), green total factor productivity (GTFP), and industry structural transformation (Industry). First, we use the number of green patent applications to measure the level of green innovation. Second, we incorporate corporate environmental pollution into the evaluation system, and use the non-radial SBM-ML index to measure green total factor productivity. The input and output indicators of green total factor productivity include factor inputs, desired outputs, and non-desired outputs. Among them, factor inputs include labor inputs, capital inputs and energy inputs. Labor input is measured by the number of employees in the enterprise; capital input is measured by the net fixed assets of the enterprise; energy inputs are converted by the industrial electricity consumption of the city where the enterprise is located according to the proportion of the enterprise's employees in the employment of urban personnel in the city; desired output is measured by the enterprise's business revenue; non-desired output is converted to industrial sulfur dioxide, industrial wastewater, and industrial dust emissions by the proportion of employees in the city where the enterprise is located. Finally, we measure the degree of industrial transformation using the share of tertiary value added in GDP.

4.1.2.5 Control variables

Following Koengkan et al. (2018), Qin and Cao (2022), Jin et al. (2021), Lee and Lee (2022), Wang et al. (2023b), we introduce a series of city-level control variables over time to minimize the impact of other factors on the empirical results. The control variables include the level of economic development (*GDP*), urbanization rate (*Urban*), population density (*Density*), fiscal expenditure (*Fiscal*), foreign investment (*Open*), energy consumption (*Energy*) and residential income (*Income*). Specifically, we use regional GDP *per capita* to measure the level of regional economic development, the ratio of urban population to total resident population to measure the urbanization rate, the total regional population divided by the total area of the region to measure the population density, fiscal expenditure divided by GDP to measure the level of regional fiscal expenditure, the amount of foreign investment divided by GDP to measure the level of openness degree, the *per capita* electricity consumption to measure the level of energy consumption, the *per capita* energy consumption to measure the level of energy consumption, and residential income disposable income *per capita* in the region the measure the residential income. The definition of the variables is shown in Table 2.

4.2 Data

Carbon emissions data. Carbon emission data include both carbon intensity and carbon efficiency data. The data sources are

TABLE 2 Variable definitions.

Variable	Symbol	Definition
Carbon emission intensity	$CarInten_1$	Measured using the sum of the three categories of carbon emissions and divided by the GDP and multiplied by 10,000
	$CarInten_2$	Apparent consumption of fuels used multiplied by the corresponding carbon conversion factor, minus the use and loss component of apparent consumption of non-energy fuels, and divided by GDP, multiplied by 10,000
Carbon emission Efficiency	$CarbonEff$	Two methods, SBM model and Non-Radial Directional Distance Function (NDDF), are used for the measurement
Green Finance	$Green$	The entropy value method is used to measure based on the constructed index
Digital Economy	$Digital$	The entropy weight method is used to find the value of the composite index based on the constructed indicators
Green Innovation	$Innovation$	Logarithm of the number of green patents filed by the enterprise
Green Total Factor Productivity	$GTFP$	Measured using the non-radial SBM-ML index
Industrial Structure Transformation	$Industry$	Value Added of Tertiary Industry as % of GDP
Economic Development	GDP	Regional GDP *per capita*
Urbanization Rate	$Urban$	Ratio of urban resident population to total resident population
Population Density	$Density$	Total regional population divided by total regional area
Fiscal Expenditure	$Fiscal$	Fiscal expenditure divided by GDP
Foreign Investment	$Open$	Amount of foreign capital used divided by GDP and multiplied by 7
Foreign Investment	$Energy$	Electricity consumption per capita in prefecture-level cities
Resident Income	$Income$	Disposable income per capita

China's statistical yearbooks, such as China Urban Statistical Yearbook, China Industrial Statistical Yearbook, and China Environmental Statistical Yearbook. In addition, some of the missing data were supplemented using the IPCC emission factor database. Emission factor data were obtained from the Provincial Greenhouse Gas Emission Inventory Guidelines (Trial) and the carbon emission inventory guidelines issued by the government.

Green finance data. The data required to measure the level of green finance come from the Statistical Yearbook and Environmental Status Bulletins of each region.

Digital economy data. The raw data for measuring the digital economy index comes from the China Urban Statistical Yearbook.

Prefecture-level data. A series of city-level control variables are introduced in the regression, and city-level mechanism variables are also introduced in the mechanism analysis. The above data come from China Urban Statistical Yearbook, China Environmental Statistical Yearbook, and provincial statistical yearbooks.

Enterprise-level data. In the mechanism analysis, we match the city-level data with enterprise micro data to analyze the impact of green finance on carbon emissions. The enterprise-level data comes from CSMAR database and websites of listed companies.

Based on the variables needed to measure carbon emissions, green finance, and digital economy, we select databases that can obtain data on these variables. In China, government statistics are the most authoritative, official, and complete database to obtain macro indicators, so we choose several Chinese statistical databases. In addition, the CSMAR database is mostly used for the study of Chinese micro-enterprises, which contains complete data on Chinese listed companies and can be updated to the most recent year. The use of the most authoritative official statistics in China and the most widely used microenterprise statistics enhances the credibility of the empirical results of the study. We process the samples as follows: (1) we exclude prefecture-level cities with missing samples; (2) we exclude four municipalities directly under the control of the central government, two special administrative regions, Taiwan Province, and the Tibet

TABLE 3 Descriptive statistics of variables.

Variable	Mean	SD.	Max	Min	Observations
$CarInten_1$	2.732	2.680	15.277	0.230	2,362
$CarInten_2$	2.324	3.123	20.119	0.120	2,362
$CarbonEff$	0.528	0.164	0.120	0.762	2,362
$Green$	0.324	0.129	0.598	0.075	2,362
$Digital$	0.118	0.081	0.562	0.036	2,362
$Innovation$	2.915	1.628	0	7.023	2,362
$GTFP$	0.996	0.011	1.039	0.853	2,362
$Industry$	0.448	0.110	0.779	0.085	2,362
GDP	5.553	3.261	17.427	1.346	2,362
$Urban$	0.561	0.142	0.757	0.273	2,362
Pop	0.042	0.029	0.130	0.001	2,362
$Fiscal$	0.212	0.112	0.407	0.182	2,362
$Open$	0.017	0.017	0.076	0.001	2,362
$Energy$	0.625	1.202	4.971	0.055	2,362
$Income$	3.179	0.986	7.057	1.600	2,362

TABLE 4 Baseline results.

Variables	Dependent variable: *CarInten*		
	(1)	(2)	(3)
Green	−4.484*** (0.656)	−2.295*** (0.582)	−1.145*** (0.413)
GDP		−0.100*** (0.020)	−0.085*** (0.019)
Urban		−1.044* (0.629)	0.064 (0.529)
Pop		−2.044 (2.438)	−2.510 (1.930)
Fiscal		4.908*** (0.776)	6.748*** (1.158)
Open		−7.799 (11.868)	−3.082* (1.709)
Energy		−0.015 (0.047)	−0.011 (0.038)
Income		−0.059 (0.049)	0.373*** (0.139)
Constant	4.170*** (0.220)	3.634*** (0.326)	0.864 (0.616)
City FE	Yes	Yes	Yes
Year FE	No	No	Yes
R^2	0.9555	0.9679	0.9711
N	2,362	2,362	2,362

Note: The standard deviation is reported in the parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Autonomous Region samples; and (3) to exclude the outlier effect, we winsorized all the continuous variables at 1% and 99%. To eliminate the effect of some extreme values on the study, continuous variables are generally subjected to winsorize. Studies usually treat extreme values at the 1% and 99% quantiles. For values less than 1%, the 1% value is assigned; for numbers greater than 99%, the 99% value is assigned. We used the econometric software Stata 17.0 in our study. The Stata commands used in this study included sum, winsor2, global, reghdfe, ivreghdfe.

4.3 Descriptive statistics

The descriptive statistics of the main variables are shown in Table 3. As can be seen from Table 3, the mean values of carbon emission intensity measured using the two methods are 2.732 and 2.324, and the standard deviations are 2.680 and 3.123, respectively, indicating that there are large differences in carbon emission intensity among Chinese prefectural-level cities. Meanwhile, the mean and standard deviation of carbon emission efficiency are 0.528 and 0.164, respectively, indicating that the carbon emission efficiency of Chinese prefectural-level cities is not high. In addition, the measured mean values of the degree of green finance development and the degree of digital economy development are 0.324 and 0.118, respectively, and the standard deviation is 0.129 economy 0.081, respectively.

5 Results

5.1 Baseline results

We use Model (1) for the baseline regression. Table 4 shows the regression results. In Table 4, Column (1) shows the regression results without introducing any control variables, Column (2) introduces control variables, and Column (3) further introduces fixed effects. When no control variables are added, the results in Column (1) show that the coefficient of *Green* is −4.484 and is significant at the 1% statistical level, indicating that green financial development can reduce carbon emission intensity, while the results in Column (2) show that the coefficient of *Green* is −2.295 after the introduction of the control variables and remains significant at the 1% statistical level. When all the control variables and city and year fixed effects are introduced, the absolute value of the coefficient of *Green* decreases to −1.145 and remains significantly positive at the 1% statistical level. Taken together, the results in Columns (1)–(3) indicate that the development of green finance significantly reduces carbon emission intensity, which verifies Hypothesis 1.

For the other variables, as can be seen in Column (3) of Table 4, the coefficient of *GDP* is −0.085 and is significant at the 1% statistical level, indicating that an increase in the level of economic development significantly reduces carbon emissions. Generally, the increase in the level of economic development may exacerbate environmental pollution. However, China has attached great importance to environmental protection and carbon emission reduction in recent years, and has proposed the goal of high-quality development to reduce environmental pollution and carbon emissions while developing the economy. Our results confirm the effectiveness of China's high-quality development. In addition, the coefficient of *Fiscal* is 6.748 and is significant at the 1% statistical level, suggesting that an increase in fiscal inputs may increase carbon emission intensity. This is because the increased fiscal investment may be used in areas that can promote economic development, such as production, manufacturing, and construction. These areas can generate many carbon emissions, thus increasing carbon emission

TABLE 5 Robustness check results.

Variables	(1)	(2)	(3)
	Dependent variable: *CarInten*		
	Alternative measure of the dependent variable	Lag one period	City-year trend
Green	−1.920*** (0.603)	−1.219*** (0.418)	−1.913*** (0.422)
Controls	Yes	Yes	Yes
City FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
R^2	2,362	2,120	2,362
N	0.9020	0.9750	0.9722

Note: The standard deviation is reported in the parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

intensity. The coefficients of *Open* and *Income* are −0.382 and 0.373 and are significant at the 10% and 1% statistical levels, respectively, which implies that increased openness up can significantly reduce carbon emission intensity, but increased *per capita* income increases carbon emission intensity.

5.2 Robustness checks

After the baseline regression, we conduct a series of robustness checks to examine the robustness of the baseline regression results.

5.2.1 Alterative measures of carbon emission intensity

In addition to the carbon emission intensity measure used in the baseline regression, we use another carbon emission intensity measure in the variable description section and conducts robustness checks based on this measure. The results of the alternative carbon emission intensity measure are shown in Column (1) of Table 5. Column (1) of Table 5 shows that the coefficient of *Green* is −1.920 and is significant at the 1% statistical level, which is consistent with the results in the baseline regression and proves the robustness of the baseline regression results.

5.2.2 Lagging the core explanatory variables by one period

Green finance, as a means of government intervention in the market, may need some time to have an impact on carbon emissions. Therefore, we include green finance lagged by one period in Model (1), so as to reconstruct Model (1) as the following model and re-regress based on this model.

$$CarInten_{i,t} = \beta_0 + \beta_1 Green_{i,t-1} + \gamma \boldsymbol{X}_{i,t} + \gamma_i + \delta_t + \varepsilon_{i,t} \quad (3)$$

where, $Green_{i,t-1}$ denotes the green finance in lag one period. Other variables are consistent with Model (1). The regression results based on Model (3) are shown in Column (2) of Table 5. The results show that the coefficient of *Green* in the lagged period is −1.219 and is significant at the 1% statistical level, indicating that the increase of green finance still reduces carbon emission intensity after considering the lagged effect of green finance, which once again proves the robustness of the baseline regression results.

5.2.3 Additional introduction of city-year trend term

Factors that change over time in a region, such as economic fluctuations, also have an impact on carbon emission intensity, and these factors differ among prefecture-level cities. Therefore, we additionally introduce a city-year trend term in Model (1) to explain the influence of possible time-varying factors among cities on the results. The regression results with the additional introduction of the area-time trend term are shown in column (3) of Table 5. The results show that the coefficient of *Green* is −1.913 and significant at the 1% statistical level, indicating that the results after the additional introduction of the city-year trend term support the baseline results, which also proves the robustness of the baseline results.

5.3 Endogenous analysis

This paper explores the impact of green finance on carbon emissions. However, if a region has a lower carbon emission intensity, its own green financial system may be better, which may lead to the reverse causality problem. Meanwhile, although we introduce many other control variables that affect carbon emission intensity to alleviate the impact of the omitted variable problem on the empirical results, it is difficult to control all the factors affecting carbon emissions and there may also be a certain measurement error problem. Therefore, we construct appropriate instrumental variables and conducts endogeneity analysis based on the two-stage least squares method.

In this paper, instrumental variables are constructed using the product of the average of the lagged one-period value of the green finance index for all prefecture-level cities in a province and the spatial distance of the prefecture-level city from the prefecture-level city with the highest green finance index in the province. A suitable instrumental variable is correlated with the endogenous explanatory variables but uncorrelated with the disturbance term, i.e., it satisfies both the correlation and exogeneity assumptions.

TABLE 6 Endogeneity analysis results.

	(1)	(2)
	The first stage	The second stage
IV	−0.010*** (0.001)	
Green		−4.941** (2.540)
Controls	Yes	Yes
City FE	Yes	Yes
Year FE	Yes	Yes
Kleibergen-Paap rk Wald F statistic		174.921
Hansen J statistic		0.000
N		2,362

Note: The standard deviation is reported in the parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

For the relevance assumption, green finance, as an innovation in the environmental regulatory system, is characterized by policy diffusion. When a prefecture-level city introduces an innovative policy, there may be imitation behavior in other prefecture-level cities, leading to the immediate-neighborhood effect of institutional innovation. Therefore, the instrumental variable constructed in this paper is correlated with the endogenous explanatory variables, and this instrumental variable satisfies the correlation assumption. In addition, the green financial development in the lagged period does not affect the degree of previous green financial development, and the spatial distance between two prefectures is a non-time-varying variable that does not affect green financial development. Therefore, the instrumental variables constructed also satisfy the exogeneity assumption of instrumental variables.

Using the constructed instrumental variables, we analyze using two-stage least squares. The results of the two-stage least squares regression are shown in Table 6. Panel A and Panel B report the first and second stage regression results, respectively. From the regression results of Panel A, the coefficient of the instrumental variable is −0.010 and significant at the 1% statistical level, which indicates that the instrumental variable is correlated with the endogenous explanatory variables, once again proving the correlation assumption of the instrumental variable. In addition, the results of Panel B show that the coefficient of *Green* is −4.941 and is significantly negative at the 5% statistical level. After the analysis using two-stage least squares, the coefficient of Green becomes smaller, indicating that the results in the baseline regression underestimate the impact of green finance on carbon emission intensity. The endogeneity analysis shows that the regression results of the two-stage least squares method using instrumental variables also prove that the development of green finance can reduce the intensity of carbon emissions, which is consistent with the results of the baseline regression.

5.4 Mechanism analysis

We construct a mediating effect model based on model (1) to identify the mediation mechanism of green finance affecting carbon emission intensity. The models are as follows:

$$Mechanism_{it} = \varphi_0 + \varphi_1 Green_{it} + \gamma \boldsymbol{X}_{it} + \gamma_i + \delta_t + \varepsilon_{i,t} \quad (4)$$

$$CarInten_{it} = \vartheta_0 + \vartheta_1 Green_{it} + \vartheta_2 Mechanism_{it} + \gamma \boldsymbol{X}_{it} + \gamma_i + \delta_t + \varepsilon_{i,t} \quad (5)$$

where *Mechanism* denotes the mediating variables, including green innovation, green total factor productivity and industrial transformation and upgrading. The independent variable in Model (4) is the green finance, and the dependent variable is the mediating variable. The model is used to test whether green finance has an impact on the mediating variables; Model (5) introduces the mediating variables on the basis of Model (1) to test whether the mediating variables have an impact on carbon emission intensity. The coefficients we are interested in are φ_1, ϑ_1 and ϑ_2. It has been proved earlier that green financial development significantly reduces carbon emission intensity, so if the coefficients of φ_1 and ϑ_2 are significant, it suggests that green innovation, green total factor productivity, and industrial transformation and upgrading are the important mechanisms through which green finance affects the carbon emission intensity.

The results of the mechanism test are shown in Table 7. Panel A and Panel B are the regression results of Model (3) and Model (4), respectively. Columns (1)–(3) are the mediating effects of green innovation, green total factor productivity and industrial transformation and upgrading, respectively. The coefficients of *Green* in Columns (1)–(3) of Panel A are 0.249, 0.031, and −0.121, and are significant at the statistical levels of 5%, 10%, and 1%, respectively, which indicates that the development of green finance significantly improves the green innovation, increases green total factor productivity, and promotes industrial transformation and upgrading. In addition, the regression results of Panel B show that the coefficients of *Innovation*, *GTFP* and *Industry* in Columns (1)–(3) are 2.009, 2.890 and −2.121 respectively, and are significant at 1%, 10% and 1% statistical levels respectively. This indicates that the increase of green innovation, green total factor productivity and industrial transformation and upgrading significantly reduces carbon emission intensity, which also means that the mediating effect of green innovation, green total factor productivity and industrial transformation and upgrading is established.

The above results show that green finance reduces carbon emission intensity by improving green innovation, increasing

TABLE 7 Mechanism analysis results.

Panel A			
Variables	(1)	(2)	(3)
	Innovation	*GTFP*	*Industry*
Green	0.249** (0.102)	0.031* (0.017)	−0.121*** (0.040)
Controls	Yes	Yes	Yes
City FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
R^2	0.6022	0.5031	0.9024
N	2,362	2,362	2,362
Panel B			
variables	Dependent variable: *CarInten*		
	(1)	(2)	(3)
Innovation	2.009*** (0.706)		
GTFP		2.890* (1.740)	
Industry			−2.121*** (0.600)
Green	−0.206 (0.438)	1.033 (1.330)	−0.007* (0.004)
Innovation	2.009*** (0.706)		
Controls	Yes	Yes	Yes
City FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
R^2	0.9787	0.9787	0.9725
N	2,362	2,362	2,362

Note: The standard deviation is reported in the parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

green total factor productivity and promoting industrial transformation and upgrading, which verifies Hypothesis 1a, Hypothesis 1 b and Hypothesis 1c.

6 The impact of green finance on carbon emission efficiency

After examining the impact of green finance on carbon emission intensity, we further analyze the impact of green finance on carbon emission efficiency. Carbon emission efficiency indicates that the maximum desired output and the minimum carbon emission can be achieved when the input factors such as capital, labor, and energy are certain, and it is a key indicator for measuring green and low-carbon development. Therefore, examining the impact of green finance on carbon emission efficiency is of great significance to comprehensively test the carbon emission reduction role of green finance. In analyzing the impact of green finance on carbon emission intensity, we use data at the prefecture-level city level. However, due to data limitations, we can only obtain provincial-level data when using both SBM and NDDF methods to measure carbon emission efficiency. Therefore, we use provincial-level data to test the impact of green finance on carbon emission efficiency in China.

The results are shown in Table 8. Columns (1) and (2) of Table 8 show the regression results of green finance on carbon emission efficiency measured by SBM and NDDF methods, respectively. The results show that the coefficients of *Green* in Columns (1) and (2) are 0.271 and 0.069, respectively, and are significant at 5% and 10% statistical levels, respectively. This indicates that the results using the two different carbon emission efficiency measures all show that the development of green finance improves carbon emission efficiency, which verifies Hypothesis 2.

The results in Table 8 also support the conclusion of the benchmark regression in Table 4. Green finance development reduces carbon emission intensity by enhancing the level of green innovation, improving green total factor productivity and promoting industrial structure transformation. In this process, carbon emission efficiency is also greatly improved, which once again verifies the positive role of green finance in realizing carbon emission reduction and environmental protection.

TABLE 8 The results of the impact of green finance on carbon efficiency.

Variable	Dependent variable: *CarEff*	
	(1)	(2)
	SBM	NDDF
Green	0.271** (0.118)	0.069* (0.039)
Controls	Yes	Yes
City FE	Yes	Yes
Year FE	Yes	Yes
R^2	0.8343	0.9542
N	1898	1898

Note: The standard deviation is reported in the parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

TABLE 9 Moderating effects analysis results.

Variable	Dependent variable: *CarInten*	Dependent variable: *CarEff*
	(1)	(2)
Green × *Digital*	−5.227* (2.921)	1.825** (0.769)
Green	0.573 (0.676)	0.023 (0.172)
Digital	1.701* (0.918)	−0.474 (0.316)
Controls	Yes	Yes
Year FE	Yes	Yes
Industry FE	Yes	Yes
R^2	0.9818	0.8372
N	1937	1897

Note: The standard deviation is reported in the parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

7 Moderating effects of digital economy

We further introduce the interaction term between green finance and digital economy based on Model (1) to investigate the moderating effect of green finance on the relationship between green finance and carbon emission intensity and efficiency, and construct the following model:

$$CarInten_{i,t} = \varphi_0 + \varphi_1 Green_{it} \times Digital_{it} + \varphi_2 Green_{it} + \varphi_3 Digital_{it} + \gamma \boldsymbol{X}_{it} + \gamma_i + \delta_t + \varepsilon_{i,t} \quad (6)$$

$$CarEff_{i,t} = \rho_0 + \rho_1 Green_{it} \times Digital_{it} + \rho_2 Green_{it} + \rho_3 Digital_{it} + \gamma \boldsymbol{X}_{it} + \gamma_i + \delta_t + \varepsilon_{i,t} \quad (7)$$

where Model (6) is used to identify the effect of digital economy on the relationship between green finance and carbon intensity; Model (7) is used to identify the effect of digital economy on the relationship between green finance and carbon efficiency; *Green* × *Digital* is the interaction term between green finance and digital economy. The definitions of the other variables are consistent with Model (1). The coefficients we are interested in are φ_1 and ρ_1. In the previous analysis, our results show that the green finance reduces carbon intensity and improves carbon efficiency. Therefore, if φ_1 is significantly less than 0, it indicates that the development of digital economy strengthens the reduction effect of green finance on carbon emission; if ρ_1 is significantly greater than 0, it indicates that the development of digital economy strengthens the promotion effect of green finance on carbon emission efficiency.

The results of the moderating effect of digital economy are shown in Table 9. Columns (1) and (2) of Table 9 demonstrate the moderating effect of digital economy on the relationship between green finance and carbon intensity and carbon efficiency, respectively. In Column (1), the coefficient of *Green* × *Digital* is −5.227 and significant at 10% statistical level, which indicates that the development of digital economy significantly strengthens the negative correlation between green finance and carbon emission intensity, which verifies Hypothesis 3a. Meanwhile, the results in Column (2) show that the coefficient of *Green* × *Digital* is 1.825 and is significant at 5% statistical level, which indicates that the development of digital economy significantly strengthens

the positive correlation between green finance and carbon emission efficiency, which verifies the Hypothesis 3 b. Overall,

8 Discussion

This study discusses the relationship between green finance, the digital economy and carbon emissions in the context of China. Reducing carbon emissions is an important issue of global concern. China is the country with the largest carbon emissions in the world, and the reduction of its carbon emissions is of great significance to the realization of global carbon emission reduction. Meanwhile, green finance has been highly valued as an important way for governments to reduce carbon emissions. This study confirms the positive effect of green finance on carbon emission reduction, which provides a reference for global carbon emission reduction, especially for many developing countries facing the choice between economic development and carbon emission reduction. In addition, with the rapid development of the digital economy, its role in promoting carbon emission reduction has also been emphasized. This study also provides a reference for better utilizing the digital economy to play the role of green finance in carbon emission reduction on a global scale.

Therefore, this study is not only conducive to promoting the development of green finance and carbon emission reduction, enhancing the efficiency of carbon emission, and realizing green and sustainable development in China, but also provides references for carbon reduction in other developing countries, which are also facing the threat of carbon emission.

The feasibility of this study has several aspects: first, the Chinese government attaches great importance to the development of green finance, regards green finance as an important tool for environmental governance, and continues to innovate green financial instruments; second, the central government of China has made "carbon neutrality and carbon peaking" a national strategic goal, and is committed to realizing this goal on schedule; third, the central government requires local government officials to consider carbon emission reduction as an important task, and this task is closely linked to the officials' future, which motivates local officials to fulfill carbon emission reduction goals. However, using green finance to reduce carbon emission needs to solve some challenges, such as insufficient financial resources for environmental protection, spillover of carbon emission reduction externalities, and conflicts between economic development and environmental protection.

9 Conclusion

Using data at the prefecture-level city level in China, this paper theoretically and empirically examines the impact of green finance on carbon emission intensity and efficiency, and further examines the moderating role of the digital economy therein. The conclusions are as follows: (1) green finance reduces carbon emission intensity; (2) green finance reduces carbon emission intensity by promoting green innovation, increasing green total factor productivity, and facilitating the transformation of industrial structure; (3) green finance improves carbon emission efficiency; (4) the development of the digital economy strengthens the reduction effect of green finance on carbon emission intensity; and (5) the development of digital finance strengthens the promotion effect of green finance on carbon emission efficiency.

10 Policy implications

Based on the above findings, we put forward the following policy recommendations to facilitate and promote the development of green finance, reduce the intensity of carbon emissions, and improve the efficiency of carbon emissions. First, regional green technology innovation should be upgraded. The government should further encourage green innovation, strengthen the development and support of green technology, and improve the quality of green innovation while improving the quantity, so as to continuously improve the innovation capacity of green technology and better utilize its role in promoting green development; second, the green total factor productivity of regions should be further enhanced. Green total factor productivity is an important intermediary linking green finance and carbon emissions. Green total factor productivity incorporates environmental factors into the input-output evaluation system and is an important indicator of production quality. The government should continuously improve the green output level of enterprises and regions, thereby promoting the improvement of green total factor productivity and better playing its role as a bridge to promote carbon emission reduction; thirdly, industrial transformation and upgrading should be promoted. The government and policymakers should continuously optimize the industrial structure, accelerate the transformation of highly polluting and energy-consuming enterprises, promote the development of the structure of polluting highly polluting and energy-consuming industries in the direction of cleanliness, advancement and greening, and guide the allocation of the factor resources of these enterprises to the tertiary industry, so as to give full play to the positive effect of upgrading the industrial structure in connecting green finance and carbon emission reduction; fourthly, the digital economy should be vigorously developed. The development of digital economy will not only apply a variety of digital technologies to the production and operation activities of enterprises, but also promote the resource allocation and efficiency of the financial industry. The government should vigorously develop the digital economy, and fully link and organically integrate it with the green financial industry. At the same time, the government should vigorously introduce the digital economy into environmental governance, carbon monitoring, carbon measurement and carbon sinks to better utilize its role in promoting carbon emission reduction.

11 Limitations and future recommendations

This paper focuses on the impact of green finance on the intensity and efficiency of carbon emissions and the moderating role of the digital economy therein. However, carbon emissions in one region may have an impact on carbon emissions in another region, which requires further analysis of the spatial spillover effects of green finance on carbon emissions. In addition, since environmental pollution and carbon emissions have market failures and require government intervention to achieve optimal allocation of resources, future research can also focus on other

government intervention policies, such as regional financial subsidy policies and tax incentives to analyze the impact of these policies on carbon emissions. At the same time, since green finance includes multiple dimensions, it is possible to compare the differences in the impact of different green financial instruments on carbon emissions, and then design a better combination of green financial instruments to reduce carbon emissions. In addition, future research can examine the moderating effect of other factors on the relationship between green finance and carbon emissions to better utilize the carbon emission reduction effect of green finance.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

WL: Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Writing–original draft. PZ: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Carbon finance and funding for forest sector climate solutions: a review and synthesis of the principles, policies, and practices

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The question of funding necessary climate actions, including those in the forest sector, to drastically reduce greenhouse gas (GHG) emissions and global warming, is important to both national governments and international agencies. The objective of this paper is to address this question by reviewing and synthesizing the economic principles associated with reducing GHG emissions, the pricing mechanisms used to achieve that goal, and the diverse practices of climate finance. Included in the carbon pricing mechanisms and practices are carbon tax, compliance and voluntary emission trading, internal pricing, and funding via issuing bonds or mobilizing public budgetary resources. Then, it proceeds to describe the roles that public and private organizations can play and have played in supporting emission reduction and removal, which serves as a vital backdrop for examining current states and relative costs of forest sector initiatives. Overall, as reported by the World Bank, only about 23% of global GHG emissions are subject to any explicit price, and 75% of the emissions that are subject to a price are charged less than $10 per tCO_2e. Market-based forest finance and international support for reducing emissions from deforestation and forest degradation have accounted for a small fraction of the total spent on climate mitigation and adaptation. Further, the more recent developments in carbon pricing and funding remain slow and disappointing. Without the right scale of green finance at the right time, however, it will be difficult to achieve the needed energy and economic transformation.

KEYWORDS

economic externality, climate finance, social cost of carbon, emission trading, carbon tax, jurisdictional funding

1 Introduction

As the global warming worsens, the need for humane society to take decisive actions to mitigate climate change (CC) has become more urgent (IPCC, 2022). Therefore, transforming the energy-use system to achieve low-carbon economic development has been a crucial thrust of international deliberation and policy (Stern, 2007; Nordhaus, 2021). Central to this deliberation and policy are the following two questions: Given the massive global investment anticipated to limit the catastrophic effects of CC by drastically reducing greenhouse gases (GHG) emissions, how can the necessary mitigation and adaptation

(M&A) actions, including those in the forest sector, be funded, and how have they been financed?

The objective of this Policy and Practice Review is to address the above two questions by pursuing two interconnected analytic tasks carefully. Our first task is to exposit the fundamental economic principles of how to reduce GHG emissions and the mechanisms used to achieve that goal through various forms of carbon pricing. Our second task is to overview the developments in designing and implementing explicit carbon pricing mechanisms and the roles public and private sectors can play and have played beyond these pricing mechanisms, in financing emission reduction and removal (ER&R) and exploring alternative energy sources.

To appreciate the magnitude of the investment required to achieve global "net-zero" GHG emissions by 2050 in line with the Paris Agreement climate targets, a recent study by McKinsey & Co. (2022) suggests that an annual global investment of $9.2 *trillion* is needed over the next 30 years[1]. That amount of expenditure, an increase of $3.5 trillion per year from what is spent today (Tyson and Weiss, 2022), must be made to transform the energy, transportation, building, manufacturing, and other sectors of the economy, as well as to protect and enhance the capacities of carbon capture and storage through land-use and other practices (IPCC, 2022, Roe et al., 2019). Thus, it is important and worthwhile to investigate the essentials of carbon finance in general and funding for forest sector climate actions in particular.

Meanwhile, there has been scant attention devoted to this subject matter. For instance, in outlining alternative ways to introduce a carbon price, the Carbon Pricing Leadership Coalition (2017) noted that "GHG emissions can be priced explicitly through a carbon tax or a cap-and-trade system. Carbon pricing can also be implemented by embedding national prices in, among other things, financial instruments and incentives that foster low-carbon programs and projects." Nonetheless, we still do not know how these alternative mechanisms of carbon pricing have been adopted and whether they have considered forest sector climate actions. Likewise, while the World Bank (World Bank, 2021; World Bank, 2023) has been tracking the *State and Trend of Carbon Pricing*, it has not covered the forest sector well. Since forests are a crucial component in the international efforts of mitigating CC (Griscom et al., 2017; IPCC, 2020), filling this knowledge gap is imperative.

Parrotta et al. (2022), in their comprehensive assessment of a decade implementation of the REDD + initiative[2], examined its evolving international finance landscape. Other than lamenting on the slow and limited funding and portraying a not-so-promising outlook, however, the authors were unable to examine funding for forest sector climate solutions more broadly, let alone the specific principles and mechanisms of carbon finance. Following an overview of the policies and practices of implementing the Paris Agreement, including nationally determined contribution (NDC) and carbon accounting, Wang et al. (2021) expounded their implications to forest sector climate actions. But at the end of that article, they noted that "[S]pace limit does not permit us to get into C[carbon] finance, as well as pricing, which we will address in the future."

Building on these, and many other, studies, we review and synthesize the policy evolution and practical developments of carbon finance and funding for forest sector climate solutions in this paper. We begin with an elaboration of the economic principles of how to reduce GHG emissions and the mechanisms used to achieve that goal through various forms of carbon pricing in Section 2. In Section 3, we summarize the recent developments in designing and implementing the carbon pricing mechanisms first, and then consider the roles that public and private sectors can play and have played, beyond explicit pricing, in financing ER&R. It is expected is that this broader and updated background will enable readers to form an adequate perspective that will help them approach forest sector climate actions more effectively. In Section 4, we delve into forest sector climate actions by examining the current states and relative costs of different initiatives, alternative means they are funded, and other relevant issues. Finally, we close with a summary of the explicit and implicit mechanisms of carbon pricing and a brief discussion of the potential opportunities for future inquiry and implementation. Whenever necessary, a box or table is included to showcase the advances of a particular mechanism of carbon pricing or to report the relevant statistics of its implementation.

In sum, the evidence reported by the World Bank (World Bank, 2021; World Bank, 2023) indicates that only about 23% of global GHG emissions are subject to any price at all, and 75% of emissions that are subject to a price are less than $10 per ton of carbon dioxide equivalent (tCO_2e). In addition, REDD+ and market-based finance of forest projects and programs have accounted for a small fraction (~3%) of the total spent on climate mitigation (Barbier et al., 2020), and the average trading price of forest carbon credits is ~$7/$tCO_2$ (Donofrio et al., 2023). Overall, while promising, the more recent developments of carbon pricing remain slow and disappointing, and the financial incentives for ER&R continue to be weak.

Before proceeding, a couple of points should be made clear. First, unlike a typical review of the academic literature, this is a Policy and Practice Review. The former tends to focus on the performances of different carbon pricing mechanisms in terms of effectiveness, efficiency, and equity (e.g., Clausing and Wolfram 2023; Yin 2024). In comparison, the latter provides "a comprehensive coverage and balanced overview of current and relevant topics related to policy, regulations, and guidelines"[3]. We have chosen to do the latter, instead of the former, largely because while both

1 This is a preliminary, aggregate estimation. There exist other aggregate and disaggregate studies. See, for example, Kotchen et al. (2023) for a disaggregate estimation that highlights the different ideas and thus realizations about emissions reduction costs between the IPCC and leading economic models.

2 REDD+ is a combination of "REDD" and "+." The former means reducing greenhouse gas emissions from deforestation and forest degradation, and latter refers to conservation of forest carbon stocks, sustainable management of forests, and enhancement of forest carbon stocks (Parrotta et al., 2022).

3 For more detail, visit https://www.frontiersin.org/journals/communications-and-networks/for-authors/article-types

types of reviews are interesting and informative, it appears that the latter is currently more pertinent and more beneficial. Plus, it seems too soon to conduct a regular literature review given that the policies and practices have not been greatly advanced yet.

Second, while the references are available from a number of classical and contemporary sources, it is challenging to collate such a vast, dynamic repository of information. Moreover, it is crucial to place the literature in a proper context and shed crucial light on how to satisfactorily confront the challenges we face in CC M&A. We hope that our efforts of reviewing the policies and practices will contribute to a timely and coherent understanding of the multitude of CC financial complexities and a more effective execution of M&A actions defined by the NDCs and other international obligations, including those in the forest sector.

2 Principles and mechanisms of carbon pricing

In his book titled *The Spirit of Green*, Professor William Nordhaus (2021) has succinctly articulated the economic theory of GHG emission as a global-scale *externality* (or public good) and the mechanisms for CC mitigation through GHG ER&R. He began by observing that CC results from the impact of GHG emission that takes place outside the market; thus, GHG emission constitutes a global-scale externality, as the cost it entails spill outside of the market worldwide and are not directly reflected in prices. For activities associated with this type of externality, the costs, benefits, and prices are not properly aligned. So, "a well-managed society will ensure that major negative externalities are corrected through government laws that promote negotiations and liability for damage through powers such as regulations and taxes (p. 19)."

He further noted that "the common theme of all externalities is that "the price is wrong," meaning that prices do not reflect social costs. In the context of CC, the *social cost of Carbon* (SCC) is the total economic cost incurred for each additional ton of CO_2 (or equivalent) emitted to the atmosphere (Nordhaus, 2019). So, he argued that a central principle for dealing with CC as a grave externality is *federalism*, which "recognizes that legal, ethical, economic, and political obligations and processes operate at different levels, and the solutions will necessarily involve various institutions and decision processes depending on the level" (Nordhaus, 2021, p. 22). In fact, many eminent economists agree that the most effective policies are to "internalize" costs and benefits. *Internalization* requires that those who generate the negative externality pay the SCC. Put differently, only if the SCC is covered by the carbon price set by societies, which deploy various mechanisms to deal effectively with spillovers, can the externality be fully internalized. The mechanisms include "market incentives, governmental regulations and fiscal penalties, organizational activities through corporate responsibility, and personal ethics for important interpersonal interactions" (Nordhaus, 2021, p. 24).

Indeed, the Paris Agreement has urged national jurisdictions, businesses, and other organizations to gear up the adoption of policies that promote carbon pricing schemes and substantially boost M&A finance (World Bank, 2021). As an indispensable part of efficient ER&R, carbon pricing is intended to incentivize changes in investment, production, and consumption patterns and to promote technological innovation and deployment that will drive down future abatement costs. More specifically, scholars have argued that carbon pricing can serve multiple functions (Stern, 2007; Rogoff, 2021):

- It signals to consumers which products and services are more carbon intensive.
- It offers incentives for investors/innovators to develop new low-carbon technologies.
- It incentivizes producers to adopt low-carbon practices, processes, and technologies.
- It provides revenues for government and business to fund investments in CC M&A.

In practice, carbon pricing can take the form of cap and trade, taxation, corporate internal pricing, and voluntary market, even though external carbon tax and cap-and-trade are the two primary policy mechanisms (Carbon Pricing Leadership Coalition, 2017). The key elements to any external pricing mechanism are to ensure that the appropriate legal framework exists, public and private sectors are adequately prepared and receptive, and most importantly, the price is appropriately set to drive the desired behavior (Stern, 2007).

Before we turn to the different mechanisms of carbon pricing, it is worth noting that the Carbon Pricing Leadership Coalition (2017) indicated that to achieve the Paris Agreement climate goal—a global temperature rise of within 1.5°C, carbon emissions should be priced at least \$40-80/tCO_2e by 2020, ramping up to \$50-100/tCO_2e by 2030. A recent study, featuring a more pragmatic approach to price carbon in the US by targeting net-zero emissions by 2050, has shown a similar result: \$34-64/tCO_2e in 2025 and \$77-124/tCO_2e in 2030 (Kaufman et al., 2020).

3 Putting a price on carbon

Here, we deliberate the specific mechanisms of putting a price on carbon. In addition to carbon tax and emission cap and trade, we also cover voluntary market, corporate internal pricing, and other relevant developments.

3.1 Carbon tax

A carbon tax is a simple and straightforward way to introduce a price for GHG emissions, and each emitter is incentivized to cut emissions to reduce its own tax burden. A carbon tax offers several advantages. First, it puts the burden of GHG emissions on polluters and drives a sharp focus on reducing emissions as well as innovating new technologies (Rogoff, 2021). If it is built within the framework of existing tax code, it can be relatively easy to implement and administer. Also, a carbon tax generates revenue that can be used to improve energy efficiency, develop clean or novel technologies like carbon capture and storage, adapt to CC effects, and/or fund nature-based climate solutions (NbS) (Pettinger, 2020; Clausing and Wolfram, 2023).

Box 1 Carbon tax in costa rica

Costa Rica introduced a 3.5% tax on fossil fuels in 1997. Today, proceeds from this carbon tax generate about $27 million per year that is administered by the country's National Forest Fund (FONAFIFO). FONAFIFO supports the conservation of mature forests, reforestation with native species, and agroforestry projects that incorporate a mix of trees with crops or grasslands. In the two decades following the implementation of the tax, Costa Rica's economy has grown an average of more than 4% per year, and the fund has disbursed $500 million to about 18,000 landowners for projects protecting at least one million hectares of mature forest and more than 71,000 ha of reforestation. Transparency and accountability are keys to the success of government agencies like FONAFIFO, along with its commitment to represent interests of indigenous people, such as the protection of 162,000 ha of territory occupied by the Cabécar and Bribri tribes (Barbier et al., 2020). As shown on its website (https://www.fonafifo.go.cr/es/), transparency pertains to open business transactions and publicly assessable information on services, assets, and expenses of FONAFIFO, and accountability means that it takes full responsibility for its actions.

To facilitate implementation, a carbon tax can be instituted as "revenue neutral," whereby the full revenue stream is returned to businesses or households in the form of rebates or other tax cuts; similarly, public monetary transfers can be used to infuse cash into targeted constituencies that do not contribute much to GHG emissions but may experience economic hardship as a result of the carbon tax (Summer et al., 2009). While the cost of a carbon tax is predictable and can be targeted to specific areas, it does not guarantee achievement of a specific net emission reduction. Further, taxes are notoriously unpopular and politically polarizing. The mere notion of a carbon tax typically evokes stiff resistance from industry and consumers, who generally dislike the idea and may neither understand nor trust in the notion of revenue neutrality (Pettinger, 2020).

Even if public resistance can be overcome, political battles are inevitable as the allocation of tax revenues is decided amongst competing interests. Contentious debate is also likely to arise when considering on whom the carbon tax is to be levied—should it be placed on upstream sources of emissions (producers) or downstream users (consumers) along the supply chains? Taxing upstream users may be easier for government agencies, but taxing downstream users may provide a more direct signal to change behaviors (Sumner et al., 2009; Xu et al., 2023). Despite its challenges, many economists, politicians, and industry leaders often favor a carbon tax as the most efficient way to drive emission reductions. Several countries, including Sweden, Switzerland, Colombia, and Costa Rica (see Box 1) and other jurisdictions, like British Columbia, have successfully reduced emissions through a tax policy, while maintaining robust economic growth (World Bank, 2021). Unlike the case of Costa Rica summarized below, however, agricultural, forestry, and other land-based sectors in many countries have not directly benefitted from their carbon tax revenues, even though certain activities in these sectors may have been somehow exempted by the policy (Donofrio et al., 2021).

3.2 Cap and trade

In contrast to a carbon tax, a cap-and-trade system, also known as an emissions trading scheme (ETS), uses market forces to drive emission reductions. While results are mixed, ETS has the distinct advantage of being more politically and socially acceptable than a carbon tax. Over 80 countries specifically mention carbon markets in their NDCs (Bayer and Aklin 2020).

In an ETS, a governmental body sets an overall limit, or cap, on carbon emissions for a given jurisdiction, and each emitter is granted permits (allowable quantities of emissions) that add up to the cap. Participants are allowed to trade emission credits or debits, provided the total emission cap is achieved for the entire community (Carbon Pricing Leadership Coalition, 2017). The key is to regulate a gradual reduction of the cap, so that polluters must make commensurate cuts in emissions; as the cap is lowered, scarcity results in an increase in the price of emission allowances. If allowances for an individual firm are unachievable or unaffordable, then that firm can pay another to help achieve its target (Naughten, 2011). This is done through purchasing carbon credits from others who operate below their permitted emissions. Participants can also offset emissions by funding projects that sequester and store carbon, such as forest sector NbS.

The basic premise of an ETS is that it does not matter if every individual polluter reduces emissions equitably, provided that total emissions for the entire jurisdiction fall within the defined cap. The desired way to achieve this objective is for firms to invest in innovation of new technologies or efficiency improvements to reduce their own emissions, and offsets serve as an enabler to help achieve this ultimate objective. In theory, market forces should result in lowest cost of emission reductions, with the idea that benefits will be enjoyed by consumers and society at large (Carbon Pricing Leadership Coalition, 2017).

While an ETS induces emissions to align with an overall cap, the price of carbon is difficult to predict as economic growth and other factors cause variability in the trading price. In addition, these schemes often fail to demonstrate measurable ER&R because industries stoke fear of economic calamity and sow doubt to successfully lobby governments to grant generous (even free) permits with limited regulation, oversight, and accountability (Canham, 2021). For example, China recently launched the world's largest ETS, representing 12% of global emissions; but due to intense industry lobbying, the initial rollout omits a formal overall emissions cap, basically rendering it ineffective in driving emission reductions (Liu, 2021). Also, many ETSs have become exceedingly complicated, often involving speculation in sophisticated financial instruments, like forward derivatives and futures, that benefit an elite class of traders and result in limited impact on actual emissions (Naughten, 2011).

Many of these shortcomings can be overcome with an aggressive cap reduction strategy and strong safeguards and enforcement designed to create robust market forces to achieve sustainable ER&R (World Bank, 2021). Today, over 30 ETS programs exist around the world, including the European Union, New Zealand, and the state of California (see Box 2).

Box 2 Carbon cap-and-trade in California, United States

In response to the failure of a US national carbon pricing bill in 2003, California spearheaded its own ETS, Assembly Bill 32 (AB-32), in 2006. AB-32 was designed to reduce GHG emissions to baseline (1990) levels by 2020 (realized in 2016) and further reduce emissions by 40% and 80%, respectively, below baseline by 2030 and 2050. California also intends to generate 100% of its electricity carbon-free and achieve economy-wide carbon neutrality by 2045. Since 2015, 85% of the state's GHG emissions have been governed by AB-32. The overall cap decreased by 3% per year between 2015 and 2020 and is designed to decrease another 5% per year by 2030. As a result, AB-32 contributed to a 5.3 percent GHG emission reduction in 2013–2017 and generated $5 billion of revenue, 35% of which was invested in low-income and environmentally disadvantaged communities (Center for Climate and Energy Solutions, 2022).

To incentivize GHG emission reductions and carbon sequestration, California Air Resources Board (CARB) issues offset credits to qualified projects pursuant to six Board-approved Compliance Offset Protocols (on livestock, ozone depletion substance, U.S. forests, urban forests, mine methane capture, and rice cultivation projects). These offsets are tradable credits that represent verified emissions reductions or removal enhancements from sources not subject to a compliance obligation in the cap-and-trade program. Compliance entities may use offset credits to meet up to 8% of their obligation for emissions through 2020; 4% of their obligation for emissions from 2021-2025; and 6% for emissions from 2026-2030. Forestry credits in the offset market surged to more than 83 MTCO2e during 2017–2019, valued at almost $1.2 billion (CARB, 2021). But two recent studies reported that carbon accumulated in offset projects to date has not been additional to what might have otherwise occurred (Badgley et al., 2022; Coffield et al., 2022). Other than the California ETS, however, few other compliance markets offer similar offsetting opportunities; meanwhile, the voluntary carbon markets have been actively pursuing forest-sector offsetting credits (Yin, 2024).

3.3 Voluntary markets

With growing pressure on companies to adopt "net-zero" emission goals as part of their corporate social responsibility (CSR), voluntary markets are becoming popular and evolving rapidly. Like compliance (ETS) markets, voluntary markets provide an alternative path for organizations to offset GHG emissions through the purchase and sale of carbon credits. But as the name implies, these are neither mandated nor regulated (World Bank, 2021). Nevertheless, voluntary markets are gaining momentum as large, reputable organizations like Microsoft and Amazon commit to net-zero targets, and American Carbon Registry and Gold Standard develop protocols for certifying ER&R projects (Donofrio et al., 2021; DeFries et al., 2022).

It is important to emphasize that effective corporate environmental, social, and governance (ESG) strategies strive for true emission reductions at the source. Unfortunately, in pursuit of "quick wins," some companies may be tempted to purchase carbon offsets, including those predicated on REDD + projects, as a substitute for reducing their own emissions (Parrotta et al., 2022). While initially attractive, this approach is not sufficient to reduce GHG emissions in the spirit of the Paris Agreement. Offsets should only be used to complement investments that abate emissions (World Bank, 2021). Furthermore, socially responsible companies look to optimize their full value chains by selecting upstream partners with low GHG emissions and/or supporting supply partners to achieve emission reductions (Xu et al., 2023). When used properly, purchasing carbon credits offers a great opportunity for companies to realize net-zero emissions across their entire value chains, while providing a funding source for offsetting projects, such as NbS.

Another question is how to ensure the trustworthiness of the large intermediaries, who are involved in the project development, verification, and certification, and thus the credibility of the transactions over voluntary markets. As found by a recent investigative report of *The Guardian*, most of the REDD + projects in Peru have failed to deliver what were promised (Zadek, 2023). So, there is an acute need for adequate supervision and regulation by certifying the certifiers and verifying the verifiers, as part of the discussion over alternative approaches to governing climate solutions. It is also relevant to consider integrating voluntary markets and other carbon projects of the private sector into a national or subnational and programs (Wang et al., 2021), which is also referred to as nesting (Yin, 2024). Hopefully, these ideas will attract the public attention, and the offset credits generated by voluntary markets will be robust and reliable.

3.4 Other financing sources

There is increasing recognition that capital in global markets must be shifted toward low-carbon activities. Effective public policy can induce research and development of new technologies to reduce emissions and should foster investments in such areas as renewable energy, increased efficiency standards, public transportation, urban planning, and land management. One could argue that current global energy policy, in the form of subsidies to the fossil fuel industry, has the opposite effect by actually promoting GHG emissions. Data for 2020 indicate that of the $634 billion in global energy sector subsidies, about 70%, or nearly $450 billion went to fossil fuels (Taylor, 2020). Clearly, this disparity must be addressed where it exists, partly by *phasing out the fossil fuel subsidies*.

On the other hand, certain jurisdictions are reluctant or unable to impose costs of ER&R directly on firms and consumers, which can lead to either inaction or to imposition of costs in other forms. A prominent example is that the US federal government has recently enacted a burst of *public spending on clean energy and innovation* in 2021 and 2022, including funding for clean energy infrastructure and investments as well as a long list of clean energy tax credits (Clausing and Wolfram, 2023). It has been reported that the 2022 Inflation Reduction Act alone would spend more than $350 billion over 10 years on clean energy tax credits and subsidies (Congressional Budget Office, 2022).

Climate or "green" bonds involve the use of fixed-income instruments designed to finance debt for climate solutions (World Bank, 2014). The global green bond market has grown from about $13 billion in 2013 (World Bank, 2014) to over $646 billion in 2021 and is expected to surpass $1 trillion in 2022 (Jones, 2022). However, bonds have limitations. Investors are not always guaranteed that their money will be spent directly on a specific project of their desire. Budget constraints or scarcity of

capital may force debtors to invest in alternative priorities. Despite these and other challenges, green bond investment continues to grow because it allows organizations to signal to investors their commitment to sustainability. Moreover, these bonds also offer investors an opportunity to diversify portfolios with an ESG agenda (Giugale, 2018). While not yet a significant source of capital for forest projects, global bond proceeds support projects such as renewable energy, transportation, building energy efficiency, land use, and the like (Jones, 2022).

The Carbon Pricing Leadership Coalition (2017) stated that "[C]arbon pricing can also be implemented by embedding notional prices in, among other things, financial instruments and incentives that foster low carbon programs and projects." One way this is done is for companies to institute their own *internal price on carbon*. This can be accomplished with an *internal carbon fee* (monetary value on carbon emissions used to generate a dedicated investment stream for ER&R projects); a *shadow price* (internal hurdle rate designed to support investments and create an internal inducement to decarbonize); or an *implicit price* (spotlights the amount spent to comply with efficiency standards or reduce emissions to alleviate carbon footprint). Regardless, the aim is to place a monetary value on GHG emissions and factor the associated costs into existing operations and future investments. Many companies also advocate this approach to help build more resilient supply chains and support CSR objectives by responding to shareholder concerns. According to the Center for Climate and Energy Solutions (2022), over 1,200 companies have either instituted or plan to implement internal carbon pricing.

In addition to domestic public and private finance in developed countries, political leaders and academic experts have stressed the urgency of *international finance* to "assist developing countries in mitigating the effects of climate change without further exacerbating their already-unsustainable debt levels" (Rogoff, 2023). Some have even called for establishing a "global green bank" or "global carbon bank," which Rogoff (2023) argues is a proposal "that rich countries must consider if they are serious about tackling climate change . . . and promoting prosperity . . . in the developing world." More broadly, just like public-private partnership can help drive innovation and investment for a sustainable future (Tyson and Weisss, 2022), international cooperation and linkage will reduce distortions in trade and capital flows and aid the efficient ER&R by promoting consistency of actions across countries (Nordhaus, 2021).

In short, in pursuing jurisdictional approaches to governing climate solutions, there is a significant role for public policy and government action to foster investment and complement roles for the private sector, multilateral development banks, international financial institutions, and concessional finance of various forms (Songwe et al., 2022).

4 Forest sector solutions

World forests are huge carbon sinks, absorbing ~15.6 billion tons of CO_2 per year; because of deforestation and other disturbances, however, they emit about half of that quantity back into the atmosphere (Harris and Gibbs, 2021). Thus, deforestation and forest degradation remains a great source of CO_2 emissions. Altogether, ~23% of anthropogenic GHG emissions currently come from the destruction or poor management of the world's forests, farms, and pasture lands (Donofrio et al., 2021). On the other hand, forest sector actions could offer over two-thirds of the cost-effective NbS necessary to hold warming to below 2.0°C and about half of the low-cost mitigation opportunities (Griscom et al., 2017).

The argument for using forest sector NbS to combat CC is compelling. Stern (2007) observed that reducing deforestation is the "single largest opportunity for cost-effective and immediate reductions of C[carbon] emissions." It is estimated that about 14% of all emission reductions required to achieve net-zero GHG emissions by 2050 could be realized at a relatively low cost (~$10/$tCO_2e$) by eliminating deforestation (McKinsey and Co, 2022). Busch et al. (2019) further showed that carbon removals from tropical reforestation between 2020 and 2050 could be increased by 5.7 billion tons of CO_2 at a carbon price of $20 per ton or by 15.1 billion tons at $50 per ton. Similar results were also reported by Austin et al. (2020). Ironically, forest ecosystem conservation only receives a small fraction (~3%) of the total amount of funds spent on climate mitigation (Barbier et al., 2020).

4.1 Supporting REDD+

The Paris Agreement "recognizes the importance of adequate and predictable financial resources . . . for reducing emissions from deforestation and forest degradation," while affirming the significance of non-carbon co-benefits, such as community livelihoods and biodiversity conservation (UNFCCC, 2020). Many developing countries rely on REDD + activities in their NDCs to achieve emission reduction targets (Duchelle et al., 2017). While effective policy should be shaped and enacted by the nations where deforestation occurs, many poor countries lack the economic resources to fund the effort (Parrotta et al., 2022). As a result, industrialized countries pledged at COP15 $100 billion a year by 2020 to help developing countries cut carbon emissions and deal with the effects of CC. To administer this fund, the Green Climate Fund (GCF) was established as the financial arm of the UNFCCC with a mandate to invest equally between M&A. Unfortunately, that pledge has not been delivered (Roberts et al., 2021). Despite a flurry of promises leading up to COP26 in Glasgow, only about $80 billion a year was committed in 2021, most in the form of public grants or loans. Also, only about 25% of the funding has been designated for adaptation projects, falling short of the GCF mandate (Timperley, 2021).

In an encouraging sign, over 100 world leaders at COP26 committed to end deforestation by 2030, including a total pledge of $19.2 billion in public and private funds (Parrotta et al., 2022). Notably, the 2021 pledge includes key players like Brazil, Russia, and China, who did not sign the 2014 declaration. In addition, the US also committed $9 billion to conserve and restore the world's forests. These commitments are critical, and the relatively low cost and high impact of REDD + programs and projects are borne out by the data. During its initial 5-year pilot (2014–2018), for instance, eight REDD + projects (mostly in the Amazon) totaling more than 100 million tCO_2e in emission reductions were funded for less than $500 million, or at a cost about $5/$tCO_2e$ (Green Climate Fund, 2022).

Box 3 China's ecosystem restoration and conservation

The Chinese government invested about 700 billion yuan ($110 billion) by 2017 in several large ERPs, such as the Sloping Land Conversion Program, the Natural Forest Protection Program, the Three-Norths Shelterbelt Program, the Beijing-Tianjin-Hebei Desertification Combating Program, and the Wildlife Protection and Nature Reserve Program (NFGA, 2018). These programs have greatly improved the ecological conditions and the local people's livelihoods (Yin, 2009). Also, the country has planned to spend about three trillion yuan ($470 billion) on nine large regional ecosystem restoration and conservation initiatives during 2021–2035, which are expected to further improve the ecological conditions and the local people's livelihoods (NFGA, 2018). When these programs/initiatives were originally construed and planned, however, carbon sequestration and storage by forest and other terrestrial ecosystems was not explicitly considered. With the country's updated NDC targets to peak GHG emissions this decade and reach carbon neutrality before 2060, nonetheless, they have attracted a great deal attention for removing carbon from the atmosphere to offset its emissions (Hou and Yin, 2022).

4.2 Market-based funding

Forest-based projects may also be funded through the sale of offsets in compliance or voluntary carbon markets. In either case, the trading of carbon credits creates two desired effects: First, market forces are leveraged to drive efficient emission reductions; second, essential investments in NbS are made. In market transactions, the process normally begins with a forest owner (land manager) who authors a program/project design document describing how the project will lead to ER&R, which may take the form of afforestation and reforestation (A&R) or improved forest management (IFM), in addition to REDD.

The project design document includes a comparison of a "business as usual" base case estimate of emissions if the project was not implemented, compared with predicted emissions resulting from the intervention (Balmford et al., 2023). It is then submitted for review under a protocol designed to verify ER&R before the project can be certified and offset credits issued. Various registries are engaged in certifying programs and projects in voluntary markets, whereas the CARB and the Regional Greenhouse Gas Initiative are examples of regulatory agencies that certify those in compliance markets (Elyse et al., 2018).

Critics point out that the process to develop offsets is slow and may overstate the impact of an intervention, especially in voluntary markets, due to one or more of the following factors: (1) the "additionality" or true net impact on emissions may be overestimated because of inaccurate BAU emissions that are derived from unrealistic scenarios (Canham, 2021; Coffield et al., 2022); (2) ER&R from protecting, rehabilitating, or reforesting one area can leak emissions to another area and result in forest degradation and deforestation or A&R that may not have occurred otherwise (DeFries et al., 2022); and (3) inadequate or inaccurate measurement, reporting and verification of forest inventory and thus carbon emission from a program or project may exaggerate its benefit (Naughten, 2011) Relatedly, in examining the uncertainties in establishing forest a BAU scenario, or forest reference level, and predicting future carbon stocks, Teo et al. (2023) highlighted the variability of local forest conditions and thus the difficulty of determining the carbon additionality. They argued for scaling up project implementation and assessment to a higher level of aggregation.

While there are active and promising trends in these markets, the overall market size and trading price remains relatively small. In 2021, the trade volume forest carbon credits peaked at 517 million tCO_2e in the voluntary markets; but it dropped precipitously to less than one-10th of that amount in 2023 (Donofrio et al., 2023). This was largely attributed to the credits' lack of credibility (Balmford et al., 2023; Zadek, 2023). Even though the average price of these credits rose to ~$7.0/tCO_2$ in 2023, it was still disappointingly low.

4.3 Jurisdictional finance

To address the inefficiency and limited capability associated with the project-oriented approach and to accelerate the pace of forest sector M&A, governments, businesses, and other players ("donors") have been increasingly engaged in carbon financing through *jurisdictional approaches*. In this case, the donor, who wishes to reduce emissions via REDD or to enhance removals via A&R or IFM, finances forest sector NbS across an entire jurisdiction, instead for a single project (Donofrio et al., 2021). The resulting payments are made to the jurisdictional authorities where the NbS are pursued.

As a core component of the CC M&A governance paradigm under the Paris Agreement (Wang et al., 2021), jurisdictional funding represents an important turning point in carbon financing because until recently, most forest results-based finance has involved market-based funding, while the designated public-sector funding has been funneled to REDD + readiness efforts (Donofrio et al., 2021). More importantly, countries have undertaken ecological restoration programs (ERPs) as part of their commitments to sustainable development. While many of these ERPs may not have been originally conceived for carbon sequestration or emission offsetting, they are now called upon to assume this additional responsibility (IPCC, 2022). With a general compatibility between carbon sequestration and storage and other ecosystem services, and the newly gained currency following the UN declaration of this decade as the Decade of Ecosystem Restoration (Cook-Patton et al., 2021), ERPs have become a "game changer" for funding ER&R. We summarize the Chinese experience in Box 3.

Jurisdictional funding has also opened new opportunities for "nesting" and "hybridizing" market-based, public, and other private alternatives; thus, it offers distinct advantages that are expected to accelerate funding of forest sector NbS (Seymour, 2020). For example, unlike project developers, governments have the authority to enforce policy and control land use change broadly, while the private sector can serve as a source of immediate results-based payments. Also, incentives for aggregating projects across a jurisdiction can mitigate the risks of non-additionality, non-permanence, and leakage, and the threats to indigenous rights (van der Gaast et al., 2017). Finally, this approach can reduce the transaction costs and uncertainties and risks associated with individual projects (Wang et al., 2021).

Table 1 shows that REDD and market-based forest finance is ramping up in recent years. As indicated by the 2017–2019 data,

TABLE 1 Major categories of forest carbon finance.

Category	2017–2019	Since 2009
GCF funded REDD programs and projects	$1,717 million ($400 million from results-based payments)	$1,935 million ($619 million from results-based payments)
Compliance market offsets	$2,334 million	$3,908 million
Voluntary market offsets	$397 million	$1,394 million

Note: Data came from Donofrio et al. (2021).

TABLE 2 Carbon pricing alternatives.

Sector	Mechanisms	Benefits	Concerns
Public	*Carbon tax*	• Simple and easy to administer	• Politically unpopular
		• Burden is on polluters	• Does not ensure ER&R targets
		• Generates revenue that can target	• Allocation of revenue is divisive
	Compliance ETS	• Leverages market forces	• Unpredictable carbon price
		• Caps emissions	• Mixed success due to special interest influence
		• Politically and socially accepted	• Complexity may exclude all but elite traders
		• Aligned with NDCs	
	Regulatory action (energy subsidies, emission standards, urban planning, etc.)	• Policy framework already exists	• Politically charged
		• High potential impact	• Difficult to adapt with changing conditions
Private &Public	*Jurisdictional finance*	• Consistent with UNFCCC/Paris Agreement	• Relatively new and untested
		• Government enforcement	• Undeveloped certification guidance
		• Mitigates risk of non-additionality, impermanence, or leakage	• Subject to budget constraint and bureaucracy
Private	*Internal C pricing* (shadow price, implicit price, etc.)	• Internal investment control	• Limited consistency and accountability
		• Sustainable business growth	• Can reduce short-term profitability
		• Support corporate social responsibility	
	Voluntary markets	• Consistent with capitalist economies	• Inconsistent accounting and certification quality of offsets
		• Enables companies with low emissions to achieve C neutrality	• May encourage avoidance of emission reductions
	Bond funding	• Company strongly reinforces commitment to sustainability	• Funding may not go to desired projects
		• Offers diversification for ESG investors	• Impact often difficult to measure
			• Budgetary trade-offs can cause conflict of priorities
	Divestment strategy	• Investments can be diverted from polluting companies or industries	• Indirect leverage that does not guarantee results

about 39% of money spent on forest projects were REDD + funded through the GCF, while 52% of global financing came through compliance markets, and only about 9% came from voluntary markets—too little to make a big difference. It should be added that this not-so-favorable situation has persisted over the last a few years. Additionally, forest carbon credits have access to compliance markets in only a few national and subnational jurisdictions, with a low range of allowed offsets—mostly <8% (Yin, 2014).

5 Summary and outlook

This paper sought to better understand the carbon pricing and financing mechanisms that are not just currently available but also required for achieving ER&R in line with the Paris Agreement climate targets. We began with an overview of the economic principles of ER&R and the mechanisms of carbon pricing and then elucidated the roles that the private and public sectors can play

and have played in financing ER&R. Finally, we examined the current state of forest-based climate actions, alternative ways they are funded, and their efficiency and effectiveness.

To sum up, although carbon pricing alone may not be adequate to induce ER&R at a pace or on the scale required to meet the Paris Agreement climate targets, it is vital to create strong incentive to drive down GHG emissions (Stern, 2007; Nordhaus, 2021), which can take a variety of forms and must be complemented by well-designed policy (World Bank, 2021). The concrete mechanisms, such as carbon tax, compliance and voluntary emission trading, internal pricing, and financing via issuing bonds or mobilizing public budgetary resources, are summarized in Table 2.

Regardless, however, it is prudent to note that we are far from the envisioned extent and level of carbon price. The prevalence and magnitude of indirect carbon pricing policies still dwarf the impact of direct carbon pricing: fossil fuel excise taxes and subsidies are worth over $1 trillion each year; at the same time, ETSs and carbon taxes raised almost $100 billion in revenues in 2022, and the voluntary carbon market came up with a total annual value in the order of $2 billion (World Bank, 2023). Only about 23% of global GHG emissions are subject to any price at all, and 75% of emissions that are subject to a price are less than $10 per tCO_2e (World Bank, 2021; Donofrio et al., 2023). Also, as of 1 April 2023, less than 5% of global GHG emissions were covered by a direct carbon price at or above the range recommended by 2030 (World Bank, 2023). The financial rewards and penalties continue to be weak in incentivizing polluters to abate their emissions (World Bank, 2023).

Going forward, not only are the various categories of financing expected to surge, but it is also believed that jurisdictional finance will emerge rapidly as public pressure to achieve carbon neutrality and ecosystem restoration mounts (Donofrio et al., 2021). The more seamlessly and comprehensively carbon pricing is introduced on a global scale and the more aggressively pricing is ratcheted up, the more effective it will be in limiting the devastating impacts of CC (Carbon Pricing Leadership Coalition, 2017). But care must be taken to ensure that the introduction of carbon pricing is done in a way that limits emissions and potential climate disruption while fostering economic growth and ecological sustainability (DeFries et al., 2022). The choice of instrument, the level of coverage, and the underpinning price can, and should be, tailored to meet the specific circumstances, priorities, and needs (World Bank, 2023).

Fortunately, there are many pricing mechanisms that have been successfully deployed to achieve these objectives, and novel approaches continue to emerge as different mechanisms are strengthened, nested, hybridized, and/or integrated. A combination of them is likely to be more efficient, effective, and even equitable (World Bank, 2021). Just like public-private partnership can help drive innovation and investment for a sustainable future (Tyson and Weisss, 2022), international cooperation and linkage will reduce distortions in trade and capital flows and aid efficient ER&R by promoting consistency of actions across countries (Nordhaus, 2021).

Finally, we highlighted the opportunities of forest sector climate solutions, including REDD+, as well as their significance and comparative advantage. As of now, however, forest sector M&A actions are inadequately linked up with or integrated into these pricing mechanisms. As more national and subnational jurisdictions look to set up domestic crediting mechanisms, the transparency and accountability in goal setting, trading, and reporting by nonstate actors must be guaranteed (UN High-Level Expert Group on Net Zero Emissions Commitments of Non-State Entities 2022b). Without sufficient credibility, the forest carbon markets, voluntary or compliant, can hardly work well.

Obviously, there are many other land-use practices than forest-based actions that can contribute to ER&R, including grassland, wetland, peatland conservation or restoration, climate-smart agriculture and agroforestry, soil conservation, and coastal restoration. These efforts should also be part of the ultimate NbS (Sato et al., 2019; IPCC, 2022). But for any land-use practices to be effective and sustainable, we must confront the risks of potential non-additionality, non-permanence, leakage, and high transaction costs and uncertainties resulting from individual projects (Badgley et al., 2022; Defries et al., 2022). Whenever feasible, some kind of pooling or aggregation via intermediary agencies or jurisdictional organizations should be pursued; accordingly, national and subnational program-based approaches are called for (Wang et al., 2021). As such, the effects of mitigating project-level risks and costs of these alternative funding and participating pathways, as well as their effectiveness, deserve closer attention (Kotchen et al., 2023).

Lastly, it should be reiterated that what we did in this paper is a Policy and Practice Review. Future work should thus consider reviewing the academic literature on the performances of different carbon pricing mechanisms when the time is appropriate and adequate empirical studies have been produced.

Author contributions

KZ: Formal Analysis, Investigation, Methodology, Validation, Writing–original draft, Writing–review and editing. DM: Conceptualization, Formal Analysis, Investigation, Validation, Writing–original draft, Writing–review and editing. RY: Formal Analysis, Investigation, Methodology, Validation, Writing–original draft, Writing–review and editing, Conceptualization, Supervision. HZ: Conceptualization, Formal Analysis, Investigation, Validation, Writing–original draft, Methodology, Supervision.

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Conflict of interest

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Research on the spatial spillover effect of carbon trading market development on regional emission reduction

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This paper introduces the current situation of carbon trading market in China and the effect of carbon emission reduction in each region. Theoretically, it expounds the influence mechanism and spatial spillover way of carbon trading market on regional carbon emission. Next, we use the data of 30 provinces in China from 2006 to 2019 to build a continuous spatial difference in difference model (SDM-DID) to empirically study the spatial spillover effect of carbon trading market on regional emission reduction. The results are as follows: First, the implementation of the pilot policy of carbon emission trading has significantly promoted the carbon emission reduction in the pilot areas. From the perspective of impact mechanism, the implementation of carbon trading pilot policy promotes carbon emission reduction in pilot areas by promoting clean transformation of energy consumption structure, improving technology absorption capacity and stimulating development of low-carbon technologies. From the perspective of spatial spillover effect, China's regional carbon emissions have significant spatial spillover effect, and carbon emissions trading has spatial spillover effect. From the perspective of spatial spillover, the carbon emission trading market promotes the carbon emission reduction in neighboring areas by promoting the clean transformation of energy structure in neighboring areas, improving technology absorption capacity and promoting technological progress.

KEYWORDS

carbon trading market, carbon emissions, carbon reduction, spatial spillover effect, regional cooperation

1 Introduction

As countries around the world pay more and more attention to environmental protection, governments have formulated relevant laws or policies to limit or reduce greenhouse gas emissions in industrial activities. At present, China has become the world's largest carbon emission country, and low-carbon transformation is imminent. The Chinese government has introduced many emission reduction policies, among which the carbon emission trading mechanism is widely used in the world as a means of carbon emission reduction. Carbon emission trading (hereinafter referred to as carbon trading) aims to promote global greenhouse gas emission reduction and reduce global carbon dioxide emissions. The carbon trading market adopts market-oriented means to achieve the purpose of controlling carbon emissions. Since June 2013, carbon trading markets have been gradually established in Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong, Shenzhen and other places. In December 2017, with the approval of The State Council, the

National Development and Reform Commission issued the "National Carbon Emission Trading Market Construction Plan (Power generation industry)", which marked the official launch of the national carbon market construction. As of 31 March 2023, the cumulative volume of carbon emission allowances in the national carbon emission rights trading market was 233 million tons, with a turnover of 10.662 billion yuan. The cumulative volume of domestic regional carbon market quota was 599 million tons, with a turnover of 16.406 billion yuan. With the continuous expansion of carbon trading scale, China's carbon trading system has gradually matured and improved.

China's carbon trading pilot has gone through 10 years, and the national carbon trading market has been established. The market is active in trading, stable in operation and has good prospects for development. The main purpose of the construction of carbon trading market is to promote regional emission reduction by market-based means, which will encourage most enterprises to achieve carbon emission reduction by various means. In this context, have carbon trading pilot areas achieved carbon emission reduction? What are the specific influencing mechanisms? Due to the rapid development of inter-regional communication and transportation, inter-regional links are becoming more and more closer. There is no geographical constraint on carbon dioxide emissions, and the geographical environment and resource endowment of neighboring regions are similar. So it is highly likely that there is a certain spatial correlation of carbon dioxide between regions. In this context, has carbon trading led to carbon reduction in other regions? Is there a spatial spillover effect of carbon reduction to promote coordinated development between regions?

The existing literature mainly studies the carbon emission trading market from the following three aspects. First, for the operation of the carbon trading market, domestic and foreign scholars have mainly conducted exploratory studies on the liquidity and effectiveness of carbon trading markets. Some scholars also evaluated the development level of carbon trading market. Yi et al. (2018) tried to construct an evaluation index system and evaluated the development of seven carbon trading pilots in China from three dimensions. Chen et al. (2020) constructed the carbon finance development evaluation index system to measure the development level of China's carbon finance. Ma and Li (2023) conducted qualitative analysis and quantitative calculation of the development status of China's carbon trading market, and on this basis, through empirical analysis, studied the reasons leading to the imbalance of regional development of China's carbon trading market. Second, for the impact of carbon market trading, Fujimori et al. (2015) used welfare losses related to climate mitigation to evaluate the effectiveness of carbon emission trading, and found that carbon emission trading can help reduce economic losses related to climate mitigation through research. Zhan and Gan (2023) adopted the staggered differential method and found that enterprises' participation in the carbon emission trading market could improve their financial performance. More scholars use DID model to evaluate the impact and mechanism of carbon trading market. For example, He (2022) empirically tested the impact of carbon trading market on enterprise innovation strategies by comprehensively applying differential and other methods. Third, for carbon trading market system and pricing, research on carbon trading price mainly focuses on the pricing of carbon emission rights and financial derivatives (Zhao et al., 2017; Lee, 2019). Hao and Tian (2020) proposed a hybrid forecasting framework for carbon price forecasting that considers multiple influencing factors, which can be used as an effective forecasting tool for carbon trading market forecasting and management.

It is very important to study the influencing factors of carbon emission to choose the path of carbon emission reduction. Most scholars conduct research from a non-financial perspective (Ren and Long, 2022). Yang (2023) pointed out that population density, urbanization level and industrial structure would promote carbon emission. A small number of scholars have studied the influencing factors of carbon emissions from the perspective of finance. Scholars have used data analysis from various countries to confirm the conclusion that financial development can promote carbon reduction. Shanhbaz et al. (2013) concluded through empirical research that Malaysia's financial development reduced carbon emissions, while energy consumption and economic growth increased carbon emissions.

As for the research on the emission reduction effect of carbon trading policy, most of the existing literature adopts the intermediary effect, DID and other methods to study carbon emission reduction. Some scholars (Liu et al., 2022; Zhang et al., 2023) found that carbon trading policy has a significant promoting effect on carbon emission reduction in pilot areas. Cheng and Xiao (2023) empirically tested the action path and generation mechanism of the impact of carbon trading policies from the perspectives of mechanism channels, spatial correlation and policy coordination. The results show that the carbon trading policy can significantly promote the carbon emission reduction in the pilot areas, and there is a certain policy expected effect. Ren and liu (2023) comprehensively evaluated the baud effect and carbon emission reduction effect of carbon trading policy based on multi-period differential method and synthetic control method. And the research results showed that carbon trading policy brought about obvious carbon emission reduction effect and Baud effect. Liu et al. (2023) studied carbon emission reduction from the perspective of the power industry. The research showed that carbon trading policy significantly promoted carbon emission reduction in the power industry, and the longer the implementation of carbon trading policy, the stronger the inhibition effect.

Currently, there are fewer studies on whether there is a spatial spillover effect of carbon emission reduction in carbon trading to drive carbon emission reduction in neighboring regions, thus promoting interregional synergistic development. Spillover effect is a dynamic process and its formation mechanism is also very complex. The main research on spillover effect includes the spillover brought about by technological innovation. For example, Wei et al. (2019) pointed out that technological innovation has spatial correlation and spatial spillover effect. Some scholars use the spatial econometric model to study the spatial spillover effect of carbon emissions. For example, Du (2023) found that the development of digital economy has a significant promoting effect on carbon emissions and a negative spatial spillover effect on carbon emissions in spatially related regions. Yuan (2023) found that there is a positive spatial correlation of carbon emissions among cities in the Yangtze River Economic Belt. The impact of digital financial development in neighboring regions on local carbon

emissions shows an inverted "U" type relationship, promoting first and then inhibiting. The enhancement of its carbon emission reduction capacity can effectively promote local carbon emission reduction. Liu and Zhong (2023) tested the spatial spillover effect and action path of carbon emission reduction through the intermediary effect test. And they found that carbon emission rights trading has positive spatial spillover effect.

Yang and Ding (2023) used SCM and S-DID methods to quantitatively analyze the policy effects and spatial effects of carbon trading policies in pilot provinces and cities. Wang and Li (2022) built a spatial difference in difference model and concluded that the adjustment of energy consumption structure formed the policy spillover effect and promoted the carbon emission reduction in neighboring regions. All these prove that the spatial difference in difference method is feasible to study the spatial spillover effect of regional emission reduction. Based on extensive reference to theories and literature results, we adopt a combination of normative theory and empirical research to explore the impact of carbon trading market on regional carbon emission reduction and spatial spillover effects. Firstly, the mechanism and spatial spillover path of carbon trading market on regional carbon emissions are explained theoretically. Then, the spatial spillover effect of carbon trading market on regional emission reduction is studied by using SDM-DID method based on spatial Dubin model. The spatial spillover effect is further disassembled by the deformation of spatial Dubin model to explore the impact of carbon trading market on carbon emissions.

To sum up, this paper has the following innovations and major contributions:

First, this paper improves the traditional differential method and adopts the continuous spatial difference in difference method. At present, most of the studies on the emission reduction effect of carbon trading are conducted by synthetic control method and DID method. Few studies consider its spatial spillover effect. By testing the spatial correlation of China's carbon emissions, we conclude that there is indeed a spatial positive correlation. The SDM-DID model is constructed to analyze the spatial spillover effect of the development of China's carbon trading market on regional carbon emission reduction, enriching the relevant research on the spatial spillover effect of carbon trading.

Second, we use the volume and turnover of carbon emission allowances to represent the development level of the carbon trading market instead of the 0–1 dummy variable, and makes an empirical analysis of the regional emission reduction spatial spillover effect of the carbon trading market. It provides theoretical support for the establishment of a national unified carbon market. At present, there are only a few studies on the spatial spillover effect of carbon trading, which mainly study the spatial spillover effect of carbon trading pilot policies. And they are impossible to measure the impact of carbon trading markets at different development levels on carbon emissions, but only the average effect of carbon trading pilot policies on carbon emissions can be investigated. In this paper, the volume and turnover of carbon emission quota are used to study its spatial spillover effect, which can not only represent the impact of policies, but also measure the impact of carbon trading markets at different levels of development on carbon emissions. It also enriches the relevant research on the spatial spillover effect of carbon trading markets. It has certain reference significance for the country to vigorously build the national carbon market and expand the scope of emission control enterprises entering the carbon trading market.

Thirdly, we put forward the idea of constructing spatial weight matrix from three dimensions: geographical distance, economic distance and new economic distance. At present, there is a lack of research on the transmission mechanism of regional emission reduction promoted by the development of carbon trading market. We construct S-DID model to estimate the emission reduction effect brought about by the increase in the development level of carbon trading. It also studies the spatial spillover mechanism of carbon emission reduction caused by the development of carbon market through energy structure, technology absorption capacity and technological progress. It has certain reference significance for provinces to formulate carbon emission reduction policies and smooth the carbon trading transmission path.

2 Theoretical mechanism

2.1 Theoretical mechanism for the development of carbon trading market to promote regional emission reduction

The main purpose of the carbon trading market is to promote emissions reduction, and most companies will adopt various ways to achieve carbon reduction. First, we need to achieve a clean transformation of the energy structure. Carbon trading encourages enterprises to optimize energy consumption structure through cost pressure, and energy consumption structure is the most direct and effective factor affecting carbon emission reduction. Under the carbon trading system, carbon emissions are endogenous emission reduction costs for enterprises. In order to reduce the marginal cost of emission reduction and obtain more marginal benefits, high energy-consuming industries such as power and steel will inevitably reduce their use of fossil energy. They will tend to use clean energy and adopt low-carbon energy to replace high-carbon energy, thus promoting carbon emission reduction in the whole region. Secondly, it will improve technology absorption capacity. The implementation of carbon trading policy will attract and cultivate high-level talents in related industries. The high-level talents often have strong technology absorption capacity and can provide more experience in carbon trading management, providing intellectual support and talent guarantee for carbon trading and carbon emission reduction in the region. Third, we should increase investment in research and development to achieve low-carbon technological innovation and technological progress. In order to achieve long-term regional carbon emission reduction and sustainable development, emission control enterprises must carry out low-carbon technology innovation, increase R&D investment, improve technological innovation level, improve production efficiency and energy utilization rate. By doing these, emission control enterprises can improve the market competitiveness, and we can promote low-carbon technological innovation in the entire region, and ultimately realize regional carbon emission reduction.

2.2 Analysis of the spatial spillover path of the development of carbon trading market to regional carbon emission reduction

The government should reasonably set the annual total carbon emission quota according to the requirements of the carbon intensity reduction target. After the quota is allocated, if the company's annual carbon emissions exceed this quota, it must buy from the government or on the carbon trading market, or it will be penalized. If it falls below this quota, it can be converted into carbon emission allowances and traded in the carbon trading market according to certain rules. Faced with the pressure of carbon emission quota restriction, trading entities are faced with two choices: First, enterprises can keep their own carbon emissions below their quotas by reducing total energy consumption, increasing investment in research and development, and using clean energy. The remaining quota can be sold to other subjects through the carbon trading market for profit. Secondly, enterprises cannot reduce their carbon emissions below the quota on their own, but can only choose to pay a fine or purchase carbon emission rights at market prices in the carbon trading market to offset the carbon emissions exceeded by their own production activities.

In summary, it is clear that most companies will adopt the first option, which is to achieve carbon reduction through various means. First, achieving a clean transformation of the energy structure. Second, attracting and cultivating high-level talents in related industries. Third, increasing investment in research and development to achieve low-carbon technological innovation and technological progress. It is highly likely that there is a certain spatial correlation of carbon dioxide between regions, and the development of carbon trading markets may have a spatial spillover effect on regional carbon emission reduction.

(1) The spillover effect of the development of carbon trading market on carbon emission reduction through the clean transformation of energy consumption structure.

In order to reduce marginal emission reduction costs and obtain more marginal benefits, emission control enterprises in pilot areas will inevitably reduce the use of fossil energy, tend to use clean energy, adopt low-carbon energy to replace high-carbon energy, and adjust the energy structure to reduce carbon emissions. Therefore, carbon trading can promote the clean transformation of energy structure in pilot areas, and the utilization of clean energy will drive neighboring areas to reduce the use of fossil energy, tend to use clean energy, adopt low-carbon energy to replace high-carbon energy, and ultimately drive the clean transformation of energy structure in neighboring areas. Yang and Ding (2023) found that carbon emission reduction could be achieved by changing the energy consumption structure. The increase in the cost of carbon emissions and the opportunity cost of carbon trading also relatively raises the marginal returns to energy structure optimization. Enterprises are prompted to shift from high-carbon fossil energy sources to cleaner and low-carbon energy sources with lower carbon emission factors, changing the regional energy consumption structure and thus realizing a reduction in carbon intensity.

(2) The spillover effect of the development of carbon trading market on carbon emission reduction through the improvement of technology absorption capacity.

Regions with higher levels of carbon trading markets will attract and train high-level talent in related industries. High-level talents often have strong technology absorption capacity and can provide more experience in carbon trading management. The development of carbon trading requires innovative thinking and creative ability, which is where high-level talents have an advantage. Talents have a wealth of knowledge and experience, and they are able to identify problems, propose low-carbon solutions, and translate them into practical low-carbon technology applications. Talents can deeply absorb the technology and provide intellectual support and talent guarantee for carbon trading and carbon emission reduction in the region. Finally, an increase in the level of carbon trading development can improve the attractiveness to high-level talents in neighboring regions, provide more experience in carbon trading management and low-carbon technology application, and provide more innovative thinking and innovation capabilities. The talents will absorb the technology in depth, thus improving the technology absorption capacity of the neighboring regions and promoting the emission reduction work in the neighboring regions.

(3) The spillover effect of the development of carbon trading market on carbon emission reduction through technological progress.

The development of carbon trading market has a significant effect on technological progress. Some scholars (Su, 2023) found that the implementation of carbon trading policy encourages enterprises to pay more attention to the research and development of new technologies and the mastery of core technologies, which positively promotes the independent innovation of enterprises to a certain extent. Cao and Su (2023) found that carbon trading policies significantly promoted carbon neutral technological innovation in pilot areas, and the promotion effect was significant in both the short and long term after the implementation of the policies. Du et al. (2021) study confirmed that each region can promote the improvement of local carbon emission efficiency by learning the carbon emission reduction technologies of neighboring regions. Increased investment in R&D and technological innovation related to energy and environmental protection can promote the development of low-carbon technologies and effectively reduce carbon emissions. Neighboring regions will also benefit from increased R&D investment, higher levels of technological innovation, and improved productivity and energy efficiency, thereby achieving technological progress and reducing carbon emissions in neighboring regions.

3 Empirical research design

3.1 Main variables

3.1.1 Explained variables

Among the seven carbon emission trading pilot regions listed above, Shenzhen is a city-level region and located in Guangdong Province. Considering the equivalence of the relevant variable data of provincial units, only the other six provinces are selected as representatives of the pilot regions in this paper. The carbon emission and carbon emission intensity (carbon dioxide emission

TABLE 1 Various energy consumption data and carbon dioxide emission coefficients.

Energy type	Average low calorific value (kJ/kg)	Reduced standard coal coefficient (kgce/kg)	Carbon content per unit calorific value (ton carbon/TJ)	Carbon dioxide emission coefficient (kg-CO_2/kg)	Carbon oxidation rate
coal	20908	0.7143	26.4	1.9903	0.94
coke	28435	0.9714	29.5	2.8604	0.93
crude oil	41816	1.4286	20.1	3.0202	0.98
fuel oil	41816	1.4286	21.1	3.1705	0.98
gasoline	43070	1.4714	18.9	2.9251	0.98
kerosene	43070	1.4714	19.5	3.0179	0.98
diesel	42652	1.4571	20.2	3.0959	0.98
liquefied petroleum gas	50179	1.7143	17.2	3.1013	0.98
natural gas	38931KJ/m3	1.33kgce/m3	15.3	2.1622k-CO_2/m3	0.99

Note: *, **, *** represent 10%, 5%, 1% significance levels.

per unit GDP) of each pilot area are used as explained variables to reflect the carbon emission in the process of pilot development. The combustion of fossil fuels is the main source of CO_2 emissions, so the final consumption of nine energy sources (see Table 1) in 30 provinces from 2006 to 2019 is selected to estimate the CO_2 emissions of each province. The calculation formula is given in Eq. 1.

$$C = \sum_{i=1}^{9} C_i = \sum_{i=1}^{9} E_i \times NCV_i \times CC_i \times COF_i \times \frac{12}{44} \quad (1)$$

Where, C_i represents the carbon dioxide emissions from the combustion of each energy source; i represents the type of energy; E_i represents the terminal consumption of each energy; NCV_i is the conversion factor, representing the energy released by consuming 1 kg of each energy; CC_i represents the carbon content per unit heat generated by the combustion of each energy; COF_i denotes the oxidation rate of carbon produced when each energy source is burned; 12 and 44 denote the molecular weight of carbon and carbon dioxide, respectively.

3.1.2 Control variables

To control the influence of other factors, referring to the existing research and considering the availability of data, we select the economic development level, industrial structure, forest coverage rate and urbanization level as control variables.

Level of economic development (ln pgdp). We select the real GDP *per capita* of each province to measure the economic development level of each province. The higher the level of economic development in a region is, the more developed the industry in the region is, and the carbon dioxide emissions increase accordingly.

Industrial structure (ln IS). We use the ratio of the added value of the secondary industry to the regional GDP to represent the industrial structure. As the proportion of the secondary industry increases, CO_2 emissions also increase.

Forest coverage rate (ln forest). The ratio of forest area to land area in each province is used to represent forest coverage. Forests can absorb carbon dioxide through plant photosynthesis to achieve carbon sequestration and reduce regional carbon emissions, thus greatly promoting carbon emission reduction.

Urbanization level (ln UP). We use the proportion of urban population in the total population to measure the level of urbanization in various regions of China. As the level of urbanization increases, household income increases and expenditure on energy goods increases with expenditure, which leads to more CO_2 emissions from households.

3.1.3 Core explanatory variables

In this paper, the interaction term (ln CV × post) between the trading volume of the carbon trading market and the dummy variable of policy time in the six pilot provinces is used as the core explanatory variable.

The quota trading volume of the carbon trading market (ln CV) is used to measure the development level of the carbon trading market in the pilot provinces. The use of carbon emission quota volume as a continuous dummy variable can not only represent the impact of policies in the region, but also measure whether carbon trading markets with different development levels have the same impact on carbon emissions.

The dummy variable of the time of the carbon trading pilot policy (post). Although the carbon trading pilot program was launched in 2011, actual trading took place after June 2013. In particular, the opening of the carbon market in the six pilot provinces of interest in this paper centered from November 2013 to June 2014, the year when carbon trading policies began to hit the pilot regions. Therefore, we take 2013 as the year when the pilot regions started to be affected by the carbon trading policy, and assigns a value of 1–2013 and the years after 2013, and a value of 0 to the years before 2013.

After the benchmark regression, the interaction term (ln CT × post) between the turnover of carbon emission trading and the dummy variable of policy time is used as the core explanatory variable for robustness test.

Data on the volume and turnover of carbon trading markets in six pilot provinces come from the WIND database.

3.1.4 The mediating variables

Energy consumption structure (ln ES). This paper uses the proportion of coal consumption in total energy consumption to measure the energy consumption structure of each region in China. Yang and Ding (2023) found that carbon emission reduction can be

achieved by changing the energy consumption structure. Compared with other energy sources, coal releases more carbon dioxide and causes more serious environmental pollution. As the share of coal consumption decreases, the transition to cleaner energy structure will promote regional carbon emission reduction.

Technology absorption capacity (ln L). The number of scientific research employees is used to represent the technology absorption capacity of a region. The more research workers a region has, the more advanced its management experience will be, and the faster it can develop and absorb low-carbon technologies, which can promote regional emissions reduction.

Technological progress (ln RD). We use the intensity of R&D expenditure of each province to measure regional technological progress. Su (2023) found that the implementation of the carbon trading policy prompted enterprises to pay more attention to the research and development of new technologies, as well as the mastery of core technologies. Cao and Su (2023) found that the carbon trading policy significantly promotes the carbon neutral technological innovation in the pilot regions, and the promotion effect is significant in the short term and long term after the implementation of the policy. The starting point for the impact of carbon trading on corporate technological innovation is R&D inputs. It will lead to direct innovation outputs, provide financing support for energy efficiency and emission reduction by signaling transformation, and promote technological innovation and progress, which will in turn contribute to carbon emission reduction. The higher the level of science and technology in a region, the more advanced its energy saving and emission reduction technology, and the carbon emissions in the region will also be reduced.

3.2 Data source

The data of GDP, added value of secondary industry, permanent resident population, urban population and rural population of each province at the end of the year are from China Statistical Yearbook and Statistical Yearbook of each province. The data of various energy consumption in each province are from China Energy Statistical Yearbook. The data of R&D expenditure intensity in each province are from China Statistical Yearbook on Science and Technology. The forest coverage of each province is from the China Forestry and Grassland Statistical Yearbook.

3.3 Descriptive statistics

In 2011, the "Notice on the Pilot Work of Carbon Emission Trading" was issued. Thereafter, China's carbon emission trading market was launched one after another. Since June 2013, carbon trading markets have been gradually established in Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong and Shenzhen, etc. The carbon emissions in the pilot areas of carbon emission trading are shown in Figure 1. 2011 is the launch time of the carbon emission trading market in seven pilot provinces, 2013 and 2014 are the years when the pilot carbon market will be launched successively, so it can be inferred that the implementation of the pilot carbon trading policy has a significant effect on carbon emission reduction.

Table 2 presents descriptive statistics of the relevant variables. It can be seen from the results in the table that the carbon emission level of the experimental group was significantly different from that of the control group during the study period. And the carbon emission, carbon emission intensity and *per capita* carbon emission of the control group were all higher than those of the experimental group. In addition, other control variables and intermediary variables were also significantly different. The experimental group's economic development level, urbanization level, foreign investment level, financial development level, research and development investment, scientific and technological personnel were higher than the control group. Compared with the control group, the experimental group had a lower proportion of secondary industry, forest coverage, and a cleaner energy structure. In view of this, in order to make the evaluation results of the spatial differential model more realistic and effective, it is necessary to impose restrictions on other factors that change over time except policy factors. In addition, all the variables used in this paper are stationary, and there is no multicollinearity in the control variables.

3.4 Metrological model setting

3.4.1 Model setting

In this study, a continuous S-DID model based on SEM, SAR and SDM was constructed. Formulas 2–4 represent SEM-DID model, SAR-DID model and SDM-DID model respectively:

$$\ln C_{it} = \beta_0 + \beta_1 \ln CV_{it} \times post_t + \beta_2 \ln x_{it} + \lambda \sum_{j=1}^{N} w_{ij}\sigma_{it} + \mu_i + \gamma_t + \varepsilon_{it} \tag{2}$$

$$\ln C_{it} = \beta_0 + \rho \sum_{j=1}^{N} w_{ij} \ln C_{it} + \beta_1 \ln CV_{it} \times post_t + \beta_2 \ln x_{it} + \mu_i + \gamma_t + \varepsilon_{it} \tag{3}$$

$$\ln C_{it} = \beta_0 + \rho \sum_{j=1}^{N} w_{ij} \ln C_{it} + \beta_1 \ln CV_{it} \times post_t + \theta \sum_{j=1}^{N} w_{ij} \ln CV_{it} \times post_t + \beta_2 \ln x_{it} + \eta \sum_{j=1}^{N} w_{ij} x_{it} + \mu_i + \gamma_t + \varepsilon_{it} \tag{4}$$

Where , $i, j = 1, 2, ..., N$. N is 30, representing 30 provinces[1] in China except Tibet, Hong Kong, Macao and Taiwan. t represents the year. β_0 is a constant term, and w_{ij} represents the i-th column and *j*th row element of the spatial weight matrix W . $\lambda \sum_{j=1}^{N} w_{ij}\sigma_{it}$ is the spatial lag term of the random error term. $\rho \sum_{j=1}^{N} w_{ij} \ln C_{it}$ is the spatial lag term of the explained variable $\ln C_{it}$. ρ represents the spatial

1 30 provinces including Hebei, Shanxi, Liaoning, Jilin, Heilongjiang, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Hunan, Guangdong, Hainan, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Inner Mongolia, Guangxi, Ningxia, Xinjiang, Beijing, Tianjin, Shanghai and Chongqing. Almost all of China's provincial administrations are included, but Tibet, Hong Kong, Macao and Taiwan are excluded due to limitations in data availability.

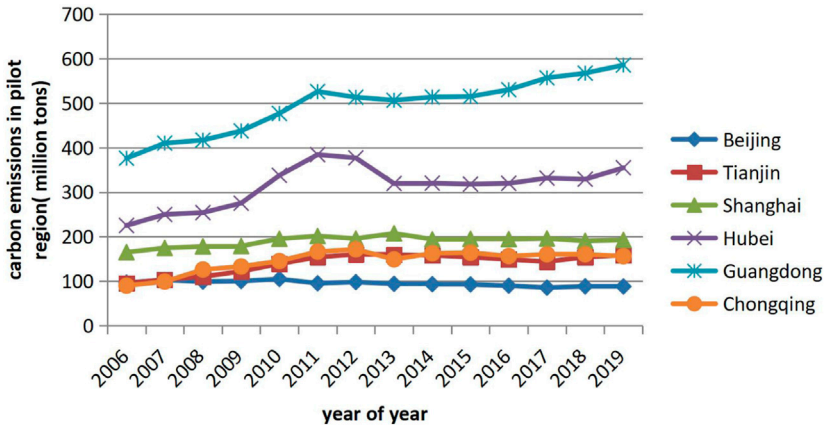


FIGURE 1
Carbon emissions of carbon trading pilot areas from 2006 to 2019.

TABLE 2 Descriptive statistical results of main variables.

Variable	Experimental group			Control group				
	Observed value	Mean value	Standard error	Observed value	Mean value	Standard error	VIF value	ADF test
ln C	84	5.271	0.568	336	5.511	0.795	-	−5.109***
ln CI	84	−13.65	0.472	336	−12.92	0.520	-	−4.966***
ln pC	84	−2.814	0.342	336	−2.699	0.527	-	−4.828***
ln IS	84	3.673	0.321	336	3.809	0.205	1.180	−5.751***
ln UP	84	4.255	0.215	336	3.901	0.190	6.480	−4.886***
ln forest	84	3.279	0.648	336	3.309	0.739	1.040	−5.600***
ln pgdp	84	10.84	0.555	336	10.22	0.510	6.370	−4.934***
ln L	84	11.80	0.774	336	10.75	1.197	7.590	−5.348***
ln fdi	84	15.33	0.841	336	14.13	1.946	2.410	−5.348***
ln finance	84	10.26	0.807	336	9.511	1.003	3.900	−2.815***
ln RD	84	0.920	0.501	336	0.0301	0.519	-	−5.173***
ln ES	84	−0.666	0.609	336	−0.0358	0.384	-	−6.069***
RD	84	2.851	1.522	336	1.170	0.583	-	−2.147***
L	84	18.04	15.63	336	8.661	10.61	-	−2.522***

Note: *, **, *** represent 10%, 5%, 1% significance levels.

autoregressive coefficient of the explained variable, and represents the spatial spillover effect of the local region on the carbon emissions of neighboring regions. C_{it} represents carbon emissions by province. $\theta\sum_{j=1}^{N} w_{ij} \ln CV_{it} \times post_t$ is the spatial lag term of the explanatory variable. θ is the spatial regression coefficient of the explanatory variable. CV_{it} is an individual dummy variable, indicating the development level of the carbon trading market in the region. CV_{it} represents t time carbon trading volume of the region i. $post_t$ is a time dummy variable. If t year is after the start of the carbon trading market in the pilot province, $post_t$ = 1; Otherwise, $post_t$ = 0. η is the spatial regression coefficient of the control variable. x_{it} is the control variable, μ_i is the individual fixed effect, γ_t is the time fixed effect, and ε_{it} is the random disturbance term.

3.4.2 Decomposition of spillover effects

The partial differential method is proposed to decompose the regression coefficient of the spatial lag term of the explained variable into direct effect, indirect effect and total effect. In this paper, the general spatial Dubin model is taken as an example. The calculate formulas are given in Eqs 5–8.

$$Y = \rho WY + X\beta + \theta WX + \tau I + \varepsilon \quad (5)$$

Move the $\rho W \ln Y$ term on the right side of the equation to the left side of the equality sign, and we get:

$$(1-\rho W)Y = X\beta + \theta WX + \tau I + \varepsilon \quad (6)$$

Multiply both sides by $(1-\rho W)^{-1}$, we get:

$$Y = (1-\rho W)^{-1}(X\beta + \theta WX) + (1-\rho W)^{-1}\tau I + (1-\rho W)^{-1}\varepsilon \quad (7)$$

The matrix of partial differential equations with respect to the Kth variable in the dependent variable is as follows:

$$\begin{bmatrix} \frac{\partial Y}{\partial X_{1k}} & \cdots & \frac{\partial Y}{\partial X_{nk}} \end{bmatrix} = \begin{bmatrix} \frac{\partial Y_1}{\partial X_{1k}} & \cdots & \frac{\partial Y_1}{\partial X_{nk}} \\ \vdots & \ddots & \vdots \\ \frac{\partial Y_n}{\partial X_{1k}} & \cdots & \frac{\partial Y_n}{\partial X_{nk}} \end{bmatrix} = (1-\rho W)^{-1} \begin{bmatrix} \beta_k & W_{12}\theta_k & \cdots & W_{1n}\theta_k \\ W_{21}\theta_k & \beta_k & \cdots & W_{2n}\theta_k \\ \vdots & \vdots & \ddots & \vdots \\ W_{n1}\theta_k & W_{n2}\theta_k & \cdots & \beta_k \end{bmatrix} \quad (8)$$

The direct effect measures the average effect of the level of development of the carbon trading market in a region on local carbon emissions, that is, the intra-regional spillover effect. It is equivalent to the average of the diagonal elements of the matrix in Eq. 8. The carbon trading volume in the non-pilot area is 0, so it has no impact on the carbon emissions in the local area. Therefore, the direct effect measures the impact of the level of carbon trading in the pilot regions on the region's carbon emissions.

The indirect effect, also known as spatial spillover effect, measures the average effect of the development level of carbon trading market in neighboring areas on the local carbon emissions, that is, the inter-regional spillover effect. It is equivalent to the off-diagonal average of the matrix in Eq. 8. The carbon trading volume in non-pilot areas is 0, so it has no impact on carbon emissions in other areas. Therefore, the spatial spillover effect in this paper measures the impact of the trading level of pilot areas on the carbon emissions of other regions.

The total effect measures the average effect of the impact of the development level of carbon trading market in all regions on the carbon emissions of the region. The carbon trading volume in the non-pilot area is 0, so it will not affect the carbon emissions of the local area or other areas. So the total effect measures the effect of the trading level in pilot regions on carbon emissions in this region and other regions.

3.4.3 Test of transmission mechanism

In order to further explore the transmission mechanism and spatial characteristics of carbon trading pilot emission reduction, we use formula (4) model as the benchmark regression model to study the transmission mechanism. In the study of carbon trading policy, economic growth, technological absorption capacity and technological progress are considered to be important factors affecting carbon emissions. In this paper, energy consumption structure (ln ES) is used to represent economic growth, the number of research employees (ln L) is used to represent population mobility, and R&D expenditure (ln RD) is used to represent technology level. Firstly, the influence of the development of carbon trading market on the above factors is analyzed, and the model is given in Eqs 9–11.

$$\ln ES_{it} = \beta_0 + \rho\sum_{j=1}^{N} w_{ij} \ln gdp_{it} + \beta_1 \ln CV_{it} \times post_t + \theta\sum_{j=1}^{N} w_{ij} \ln CV_{it} \times post_t + \beta_2 \ln x_{it} + \eta\sum_{j=1}^{N} w_{ij} x_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (9)$$

$$\ln L_{it} = \beta_0 + \rho\sum_{j=1}^{N} w_{ij} \ln L_{it} + \beta_1 \ln CV_{it} \times post_t + \theta\sum_{j=1}^{N} w_{ij} \ln CV_{it} \times post_t + \beta_2 \ln x_{it} + \eta\sum_{j=1}^{N} w_{ij} x_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (10)$$

$$\ln RD_{it} = \beta_0 + \rho\sum_{j=1}^{N} w_{ij} \ln RD_{it} + \beta_1 \ln CV_{it} \times post_t + \theta\sum_{j=1}^{N} w_{ij} \ln CV_{it} \times post_t + \beta_2 \ln x_{it} + \eta\sum_{j=1}^{N} w_{ij} x_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (11)$$

4 Empirical results and analysis

4.1 Spatial correlation analysis

4.1.1 Analysis of global Moran index

Table 3 and Figure 2 show the global Moran index of carbon emissions of 30 provinces from 2006 to 2019. It can be seen that in the sample interval from 2006 to 2019, the Moran's I index of carbon emissions in 30 provinces is significantly greater than 0, and the standardized test value Z is positive and almost all of them are greater than 1.96. This shows that during the sample period, the global Moran's index of carbon emissions in 30 provinces in China shows significant positive spatial correlation, and the spatial distribution of carbon emissions in China shows spatial agglomeration characteristics, with the possibility of spatial spillover. That is to say, the carbon emissions in this region will have a great impact on the carbon emissions in other regions. Therefore, when studying the effect of carbon trading market development on regional emission reduction, it is very necessary to consider spatial heterogeneity, and the selection of spatial econometric models can make the research results more reasonable and accurate.

4.1.2 Local Moran scatter plot

The global Moreland index can only reflect that China's regional carbon emissions are spatially positively correlated on a global scale, but the local spatial characteristics are not shown. Therefore, we further use the local Moreland scatter plot to test the local spatial correlation of regional carbon emissions, and draws the Moreland scatter plot from three time nodes in 2006, 2013, and 2019. Seeing Figures 3–5, the horizontal coordinate represents the carbon emission in the current year, and the vertical coordinate represents the carbon emission weighted by the geospatial weight matrix, that is, the spatial lag term of carbon emission. In the first and third quadrants, high values and high values, low values and low

TABLE 3 Global autocorrelated Moran's I index of carbon emissions.

Time			2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
carbon emission	Geographic distance matrix	I	0.150	0.153	0.164	0.159	0.161	0.163	0.162	0.172	0.170	0.161	0.162	0.163	0.173	0.167
		Z	1.967	1.999	2.113	2.051	2.075	2.089	2.083	2.189	2.158	2.073	2.078	2.077	2.199	2.128
		P	0.025	0.023	0.017	0.020	0.019	0.018	0.019	0.014	0.015	0.019	0.019	0.019	0.014	0.017
	Economic distance matrix	I	0.201	0.205	0.198	0.196	0.188	0.175	0.168	0.150	0.152	0.153	0.150	0.152	0.122	0.122
		Z	2.553	2.593	2.520	2.483	2.391	2.251	2.183	1.982	1.997	2.022	1.985	1.994	1.690	1.685
		P	0.005	0.005	0.006	0.007	0.008	0.012	0.015	0.024	0.023	0.022	0.024	0.023	0.046	0.046
	new Economic distance matrix	I	0.150	0.153	0.164	0.159	0.161	0.163	0.162	0.172	0.170	0.161	0.162	0.163	0.173	0.167
		Z	1.967	1.999	2.113	2.051	2.075	2.089	2.083	2.189	2.158	2.073	2.078	2.077	2.199	2.128
		P	0.025	0.023	0.017	0.020	0.019	0.018	0.019	0.014	0.015	0.019	0.019	0.019	0.014	0.017

values are clustered, reflecting the spatial dependence. In the second and fourth quadrants, low values and high values, high values and low values are aggregated, reflecting the spatial dispersion. It can be seen that most provinces and cities are clustered in one or three quadrants, which also partially confirms the spatial aggregation effect of carbon emissions. From the perspective of development trend, from 2005 to 2013 and then to 2019, all provinces gradually shifted to the third quadrant, which indicates that more and more provinces' carbon emissions gradually decreased. And more importantly, carbon emissions gradually tended to decrease.

4.2 Analysis of results of spatial econometric model

4.2.1 Baseline regression (SDID) analysis

In order to be precise and accurate, SAR-DID, SEM-DID and SDM-DID models were used respectively for regression. According to the regression results, the coefficients of spatial lag terms of both SAR-DID model and SDM-DID model are significantly positive, indicating that the development of carbon emission trading market has policy spillover and diffusion effects on regional carbon emissions. The coefficients of ln CV × post, the core explanatory variables of the three models are significantly negative at the level of 1%, indicating that with the increase of carbon emission trading volume, carbon emissions decrease. That is, the development of carbon trading market effectively promotes the emission reduction in the region. In addition, LM test and Robust LM test are both significant, and SDM-DID model is the most appropriate choice at this time.

Columns (3), (6) and (9) in Table 4 list the regression results of SDM-DID model based on three spatial weight matrices. Among them, the coefficients of ln CV × post, the core explanatory variables are significantly negative at the level of 1%, indicating that with the increase of carbon emission trading volume in the pilot area, the emission reduction effect has been achieved in the region. The spatial lag coefficient ρ of the explained variable ln C are significantly positive, indicating that carbon emissions have a transboundary conduction effect. The reduction of carbon emissions in the pilot area will significantly promote the reduction of carbon emissions in neighboring areas. The spatial lag coefficients of ln CV × post, the core explanatory variables are all significantly negative at the level of 1%, indicating that the increase in the trading volume of carbon emission rights in the pilot region significantly reduces the carbon emissions of neighboring regions. It indicates that the development of carbon trading market between neighboring regions can form a spatial spillover effect, and the development of carbon trading market can drive carbon emission reduction in neighboring regions.

4.2.2 Decomposition of spatial spillover effect

According to formula 7 of the partial differential equation, the regression coefficient can be decomposed into direct effect, indirect effect and total effect. The indirect effect is the spatial spillover effect, and the specific calculation results are shown in Table 4. As can be seen from the table, in the SDM-DID regression based on geographic matrix, the direct effect of carbon emission rights trading market is −0.0126 and the spatial spillover effect is −0.0200. In the SDM-DID regression based on economic

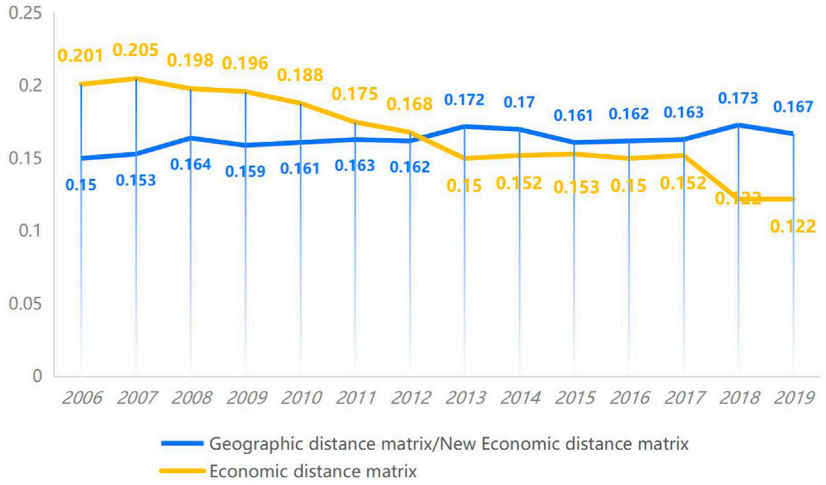


FIGURE 2
Global autocorrelated Moran's I index of carbon emissions.

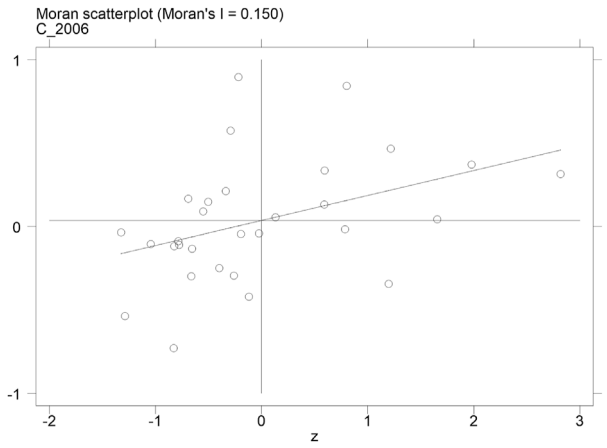


FIGURE 3
Local Moran scatter plot of regional carbon emissions in China in 2006.

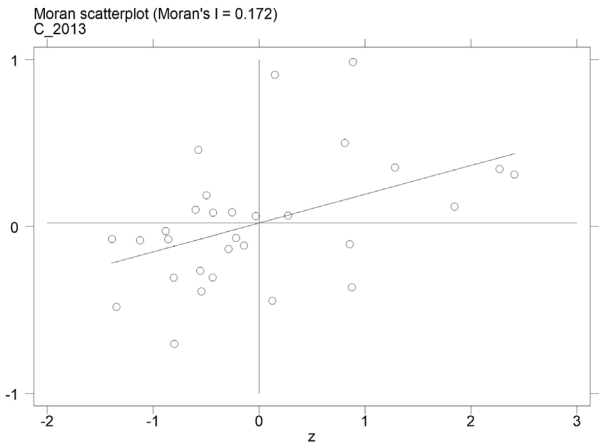


FIGURE 4
Local Moran scatter plot of regional carbon emissions in China in 2013.

matrix, the direct effect of carbon emission rights trading market is −0.0121 and the spatial spillover effect is −0.0192. In the SDM-DID regression based on the spatial weight matrix of the new economic distance, the direct effect of the carbon emission right trading market is −0.0127, and the spatial spillover effect is −0.0206, both of which are significant at the 1% level. It indicates that the increase of carbon emission right trading volume has an emission reduction effect on the pilot provinces, and also has an emission reduction effect on the neighboring provinces.

4.3 Robustness test

In order to verify the robustness of the benchmark regression results in this chapter, the accuracy of key conclusions is ensured as much as possible. In this section, methods such as replacing core explanatory variables, adding control variables, and eliminating policy years will be adopted in order to eliminate the possibility that these factors lead to inaccurate baseline regression results.

4.3.1 Change the core explanatory variable

The logarithm and time dummy variable (ln CV × post) of carbon trading volume in the pilot region is used as the core variable for benchmark spatial regression. In order to test the stability of the model, the logarithm of the carbon trading volume in the pilot areas and the time dummy variable ln CT × post is used as the core variable. The regression results are shown in Table 5. It can be seen that based on the three spatial weight matrices, the coefficients of ln CT × post are significantly negative at the level of 1%, indicating that the increase in the trading volume of carbon emission rights in the pilot area has an emission reduction effect in the region. The spatial lag coefficient ρ of the explained variable ln C are significantly positive at the level of 1%, and both the direct effect and the spatial spillover are significantly negative at the level of 1%. It shows that the increase in carbon

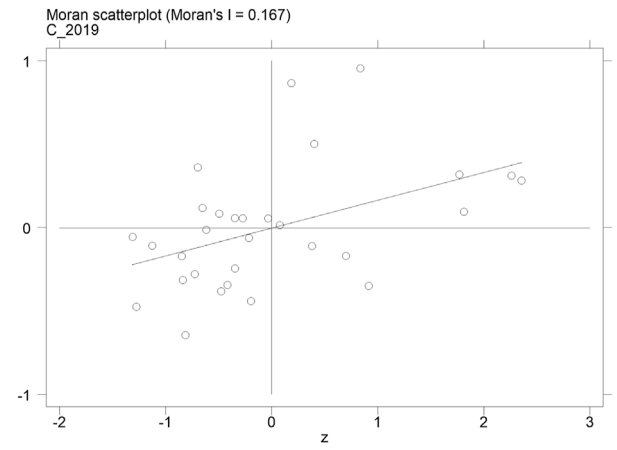


FIGURE 5
Local Moran scatter plot of regional carbon emissions in China in 2019.

emissions trading volume has an emission reduction effect on the pilot provinces and also on the neighboring provinces. There is no substantial change from the baseline SDM-DID results, so the regression results are robust.

4.3.2 Increase control variables

In view of the large differences in various aspects in different regions, we add two control variables, namely the number of scientific research employees (ln L) and foreign direct investment (ln fdi), to carry out regression on the basis of the original control variables. The regression results are shown in Table 6. It can be seen that, based on the three spatial weight matrices, the coefficients of ln CV × post are all significantly negative at the level of 1%. The spatial lag coefficient ρ of the explained variable ln C are significantly positive at the level of 1%, and the direct effect and spatial spillover effect are significantly negative at the level of 1%. There is no substantial change compared with the benchmark SDM-DID results, so the regression results are robust.

4.3.3 Excluded policy year

In order to eliminate the possible measurement error, the policy implementation year 2013 is eliminated from the sample research interval. The regression results are shown in Table 7 after excluding the samples in 2013. Based on the three spatial weight matrices, the coefficients of ln CV × post are significantly negative at the level of 1%, the spatial lag coefficient ρ of the explained variable ln C are significantly positive at the level of 1%, and the direct effect and spatial spillover effect are significantly negative at the level of 1%. It has no substantial change compared with the benchmark SDM-DID results. Therefore, the regression results are robust.

4.4 The development of carbon trading market promotes the transmission path of carbon emission reduction

In order to further explore the transmission mechanism and spatial characteristics of carbon trading pilot emission reduction, we use the general spatial Dubin model as the benchmark regression model to study the transmission mechanism, and adopts the geographical distance matrix for regression. The regression results are shown in Table 8.

(1) Energy structure. The coefficient of the core explanatory variable is significantly negative at the level of 1%, indicating that the increase in the trading volume of carbon emission rights promotes the clean transformation of the energy structure. The spatial lag coefficient of the explained variables is significantly negative at the level of 5%, indicating that there is a cross-border conduction effect of the energy structure, and the clean transformation of the energy structure in the pilot region will significantly promote the clean transformation of the energy structure in neighboring regions. The direct effect is −0.0283, and the spatial spillover effect is −0.0339, both at the level of 1%, which indicates that the increase of carbon emission trading volume promotes the clean transformation of energy structure in the region and in neighboring regions.

China's energy consumption structure is dominated by coal, and coal combustion is the main source of carbon emissions. With the reduction of coal consumption, the energy structure has gradually changed to a cleaner direction, and the carbon dioxide released under the premise of the total energy consumption remains unchanged. Therefore, the improvement of the development level of carbon trading can promote the emission reduction in neighboring areas by promoting the clean transformation of the energy structure.

(2) Technology absorption capacity. The coefficient of the core explanatory variable is significantly positive at the 1% level, indicating that the increase in the volume of carbon emissions trading improves technological absorptive capacity. The spatial lag coefficient of the explanatory variables is significantly positive, indicating that there is a cross-border transmission effect of scientific research talent, and the number of scientific research talent in the pilot region will increase significantly in neighboring regions. The direct effect is 0.378 and the spatial spillover effect is 0.575, which are both significant at the 1% level, indicating that the increase in the volume of carbon emissions trading improves the technology absorption capacity in the region and neighboring regions.

(3) Technological progress. The coefficient of the core explanatory variable is significantly positive at the level of 1%, indicating that the increase in the trading volume of carbon emission rights promotes technological progress. The spatial lag coefficient of the explained variables is significantly positive, indicating that there is a cross-border conduction effect of scientific research talents, and the number of scientific research talents in the pilot area will significantly increase in the adjacent area. The direct effect is 0.0231, and the spatial spillover effect is 0.0367, both of which are significant at the level of 1%, indicating that the increase of carbon emission trading volume promotes the technological progress of both the local and neighboring regions. Technological advances allow companies to use energy more efficiently, thus releasing less carbon dioxide during normal production activities. Therefore, the improvement of the development level of carbon trading can promote the

TABLE 4 Regression results of spatial double difference model.

Variable	W_{ij}^{d}			W_{ij}^{e}			Variable	W_{ij}^{n}		
	SAR-DID	SEM-DID	SDM-DID	SAR-DID	SEM-DID	SDM-DID		SAR-DID	SEM-DID	SDM-DID
	(1)	(2)	(3)	(4)	(5)	(6)		(7)	(8)	(9)
ln *CV* × *post*	−0.013***	−0.012***	−0.012***	−0.012***	−0.011***	−0.011***	ln *CV* × *post*	−0.0124***	−0.0122***	−0.0117***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)		(0.002)	(0.002)	(0.002)
W × ln *CV* × *post*			−0.010***			−0.010	W × ln *CV* × *post*			−0.013***
			(0.004)			(0.006)				(0.004)
ρ	0.388***		0.338***	0.386***		0.359***	ρ	0.330***		0.268***
	(0.062)		(0.065)	(0.059)		(0.062)		(0.052)		(0.056)
λ		0.366***			0.330***		λ		0.215***	
		(0.097)			(0.078)				(0.075)	
LM-lag	490.593***			292.299***			LM-lag	339.565***		
Robust LM-lag	27.422***			62.251***			Robust LM-lag	25.027***		
LM-error	549.385***			253.822***			LM-error	361.457***		
Robust LM-error	86.214***			23.774***			Robust LM-error	46.919***		
direct effect	−0.013***		−0.013***	−0.012***		−0.012***	direct effect	−0.013***		−0.013***
	(0.002)		(0.002)	(0.002)		(0.002)		(0.002)		(0.002)
indirect effect	−0.008***		−0.020***	−0.007***		−0.019**	indirect effect	−0.006***		−0.021***
	(0.002)		(0.005)	(0.002)		(0.008)		(0.001)		(0.005)
total effect	−0.021***		−0.033***	−0.019***		−0.031***	total effect	−0.018***		−0.033***
	(0.004)		(0.006)	(0.003)		(0.009)		(0.003)		(0.005)
Constant	−1.803***	−1.351**	−2.100***	−2.124***	−2.018***	−2.273***	Constant	−1.869***	−1.736***	−2.243***
	(0.387)	(0.527)	(0.402)	(0.381)	(0.450)	(0.393)		(0.384)	(0.471)	(0.398)
control variable	control	control	control	control	control	control	control variable	control	control	control
time effect	control	control	control	control	control	control	time effect	control	control	control
individual effect	control	control	control	control	control	control	individual effect	control	control	control
N	420	420	420	420	420	420	Observations	420	420	420
R-squared	0.230	0.196	0.209	0.273	0.183	0.248	R-squared	0.282	0.207	0.239

Note: *, **, *** represent 10%, 5%, 1% significance levels.

emission reduction of neighboring areas by promoting the technological progress of neighboring areas.

In the previous studies on the emission reduction effect of carbon trading policy, most scholars only came to the conclusion that carbon trading policy can significantly promote carbon emission reduction in pilot areas (Liu et al., 2022; Zhang et al., 2023). At present, a few scholars only come to the conclusion that there is spatial spillover effect of carbon emission reduction in carbon trading to drive carbon emission reduction in neighboring areas, but the research on specific transmission mechanism is still lacking (Du, 2023; Yang and Ding, 2023; Yuan, 2023). The empirical results show that the implementation of the pilot policy of carbon emissions trading has significantly promoted the carbon emission reduction in the pilot areas. China's regional carbon emissions have a significant spatial spillover effect. The carbon emissions trading market promotes the carbon emission reduction in neighboring areas by promoting the clean transformation of energy structure in neighboring areas, improving technology absorption capacity and promoting technological progress.

5.Conclusions and policy implications

5.1 Conclusions

China gradually launched a pilot carbon trading program in 2013, and officially launched a national carbon trading market in July 2021. Exploring the impact of the development of carbon trading market on

TABLE 5 Regression results of SDM-DID with changing core variables.

Variable	W_{ij}^{d}	W_{ij}^{e}	W_{ij}^{n}
	(1)	(2)	(3)
$\ln CT \times post$	−0.011***	−0.010***	−0.010***
	(0.002)	(0.002)	(0.002)
$W \times \ln CT \times post$	−0.010***	−0.009	−0.013***
	(0.004)	(0.006)	(0.004)
ρ	0.329***	0.355***	0.262***
	(0.066)	(0.062)	(0.056)
Constant	−2.149***	−2.302***	−2.284***
	(0.402)	(0.394)	(0.399)
direct effect	−0.011***	−0.010***	−0.011***
	(0.002)	(0.002)	(0.002)
indirect effect	−0.005***	−0.005***	−0.004***
	(0.002)	(0.002)	(0.001)
total effect	−0.016***	−0.016***	−0.014***
	(0.003)	(0.0030)	(0.003)
control variable	control	control	control
time effect	control	control	control
individual effect	control	control	control
Observations	420	420	420
R-squared	0.207	0.249	0.237

Note: *, **, *** represent 10%, 5%, 1% significance levels.

TABLE 6 Regression results of SDM-DID with added control variables.

Variable	W_{ij}^{d}	W_{ij}^{e}	W_{ij}^{n}
	(1)	(2)	(3)
$\ln CV \times post$	−0.014***	−0.014***	−0.014***
	(0.002)	(0.002)	(0.002)
$W \times \ln CV \times post$	−0.015***	−0.013**	−0.018***
	(0.004)	(0.006)	(0.004)
ρ	0.248***	0.243***	0.166***
	(0.064)	(0.064)	(0.056)
Constant	−8.117***	−7.672***	−8.139***
	(0.678)	(0.696)	(0.707)
direct effect	−0.014***	−0.015***	−0.015***
	(0.002)	(0.002)	(0.002)
indirect effect	−0.024***	−0.021***	−0.023***
	(0.004)	(0.007)	(0.004)
total effect	−0.038***	−0.035***	−0.038***
	(0.005)	(0.007)	(0.004)
control variable	increase	increase	increase
time effect	control	control	control
individual effect	control	control	control
Observations	420	420	420
R-squared	0.759	0.760	0.749

Note: *, **, *** represent 10%, 5%, 1% significance levels.

China's regional carbon emissions and its action path can provide basis for improving the construction of carbon trading market and promoting regional carbon emission reduction. This paper firstly introduces the development status of China's carbon trading market and the emission reduction effect of each region, and theoretically expounds the influence mechanism and spatial spillover path of the development of carbon trading market on regional carbon emissions. Then, using the data of 30 provinces in China from 2006 to 2019, the spatial difference in difference model (SDM-DID) was constructed to conduct an empirical analysis of the spatial spillover effect of carbon trading market development on regional emission reduction. The results are as follows:

First, from the viewpoint of spatial spillover effect, China's regional carbon emissions have a significant spatial spillover effect, and carbon emissions trading has a spatial spillover effect. That is, the development of the carbon trading market can not only promote the emission reduction of the pilot region, but also significantly promote the carbon emission reduction of the neighboring regions.

Secondly, from the perspective of spatial spillover mechanism, the development of carbon trading market promotes the carbon emission reduction in neighboring regions by promoting the clean transformation of regional energy structure, improving technology absorption capacity and technological progress. First of all, the increase in the trading volume of carbon emission rights in the pilot areas not only promotes the clean transformation of the local energy structure but also promotes the clean transformation of the energy structure in the neighboring areas, thus promoting the carbon emission reduction in the surrounding areas. Next, the increase in the trading volume of carbon emission rights in the pilot areas not only improves the technology absorption capacity of the local area but also improves the technology absorption capacity of the neighboring areas. The high-quality talent reserve provides intellectual support and talent guarantee for carbon trading and the realization of carbon sect in other areas, thus promoting the carbon emission reduction in the surrounding areas. Finally, the increase in the trading volume of carbon emission permits in the pilot region promotes technological progress in both the region and the neighboring region. Technological progress improves the energy utilization efficiency of enterprises, thus promoting carbon emission reduction in surrounding areas, providing theoretical support for the realization of interregional carbon trading market connectivity and the development of low-carbon technology innovation cooperation.

5.2 Policy implications

Based on the above research conclusions, the following policy implications can be drawn: First, from the perspective of carbon market construction, the construction and improvement of national

TABLE 7 Regression results of SDM-DID model excluding policy years.

Variable	(1) W_{ij}^{d}	(2) W_{ij}^{e}	(3) W_{ij}^{n}
$\ln CV \times post$	−0.013***	−0.013***	−0.013***
	(0.002)	(0.002)	(0.002)
$W \times \ln CV \times post$	−0.008**	−0.008	−0.011***
	(0.004)	(0.006)	(0.004)
ρ	0.347***	0.358***	0.272***
	(0.069)	(0.065)	(0.058)
Constant	−2.038***	−2.251***	−2.204***
	(0.417)	(0.407)	(0.414)
direct effect	−0.014***	−0.013***	−0.014***
	(0.002)	(0.002)	(0.002)
indirect effect	−0.018***	−0.018**	−0.019***
	(0.006)	(0.009)	(0.005)
total effect	−0.032***	−0.031***	−0.033***
	(0.006)	(0.010)	(0.006)
control variable	control	control	control
time effect	control	control	control
individual effect	control	control	control
Observations	390	390	390
R-squared	0.206	0.253	0.241

Note: *, **, *** represent 10%, 5%, 1% significance levels.

TABLE 8 Conduction mechanism test.

Explained variable	ln *ES*	L	RD
	(1)	(2)	(3)
$\ln CV \times post$	−0.029***	0.348***	0.021***
	(0.003)	(0.080)	(0.003)
$W \times \ln CV \times post$	−0.041***	0.264*	−0.002
	(0.006)	(0.151)	(0.005)
ρ	−0.133*	0.351***	0.689***
	(0.074)	(0.071)	(0.049)
Constant	−1.355**	−41.540**	−0.792
	(0.566)	(16.570)	(0.599)
direct effect	−0.028***	0.378***	0.023***
	(0.003)	(0.083)	(0.003)
indirect effect	−0.034***	0.575**	0.037**
	(0.005)	(0.238)	(0.018)
total effect	−0.062***	0.953***	0.060***
	(0.005)	(0.267)	(0.020)
control variable	control	control	control
time effect	control	control	control
individual effect	control	control	control
Observations	420	420	420
R-squared	0.387	0.268	0.362

Note: *, **, *** represent 10%, 5%, 1% significance levels.

unified carbon trading market should be accelerated. The implementation of the pilot carbon emission trading policy can significantly promote the emission reduction in the pilot areas and achieve the goal at the beginning of the implementation of the policy. Therefore, the construction and development of the carbon trading market should be firmly supported. Second, from the perspective of carbon emission reduction, more enterprises should be encouraged to participate in carbon emission trading. Due to the spatial spillover effect of carbon emission trading, and with the growth of carbon emission trading volume and trading volume, it can not only promote the emission reduction in pilot areas, but also significantly promote the carbon emission reduction in surrounding areas. Therefore, it is suggested to gradually expand the scope of emission control enterprises and promote the growth of carbon trading scale, so as to promote the realization of carbon emission reduction in various regions. Third, from the perspective of energy structure, we should vigorously promote the clean transformation of energy structure. Clean energy can be developed selectively according to the situation of different regions. For example, solar energy can be developed in areas with long sunshine time, wind energy can be developed in areas with strong wind power, and hydropower can be developed in coastal cities, so as to reduce the use of fossil energy (such as coal, etc.) with high unit carbon emissions and promote carbon emission reduction. Fourth, from the perspective of technological progress, investment in research and development should be increased to promote technological research and development of enterprises and low-carbon technological innovation. Low-carbon technology innovation is the most effective solution for enterprises to achieve carbon emission reduction. The government can also encourage technological innovation by giving incentives to enterprises that develop new technologies. Finally, from the perspective of interregional cooperation, we should pay attention to the joint governance of interregional carbon emissions and realize the coordinated emission reduction between regions. China's regional carbon emissions have a significant spatial spillover effect in space. Provincial governments should formulate carbon emission reduction policies according to local conditions, give full play to the policy incentive role, and promote carbon emission reduction in their own provinces and neighboring regions.

5.3 Limitations and future prospects

(1) There are many factors affecting carbon emissions. Referring to previous literature and considering the availability of data, we only select four control variables. And there may still be variables affecting carbon emissions that have not been taken into account, which will be perfected in the subsequent research to make the results of the paper more convincing.

(2) Restricted by the availability of data, the data used in this paper is only up to 2019, and the subsequent research will continue to update the data and continue to study the carbon emission reduction effect of the carbon trading market.
(3) This paper mainly studies the spatial spillover effect of the carbon trading market on regional emission reduction, and will conduct further research on regulation analysis and comparative analysis to make the study more comprehensive.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

YC: Writing–review and editing, Writing–original draft, Conceptualization, Investigation, Project administration, Software, Data curation. WF: Writing–review and editing, Writing–original draft, Investigation, Visualization, Methodology, Software. XG: Writing–original draft, Writing–review and editing, Conceptualization, Data curation, Formal Analysis, Methodology, Project administration, Supervision, Validation, Visualization, Funding acquisition.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Research on the relationship between carbon performance and financial performance of electric power enterprises under the background of "dual carbon"

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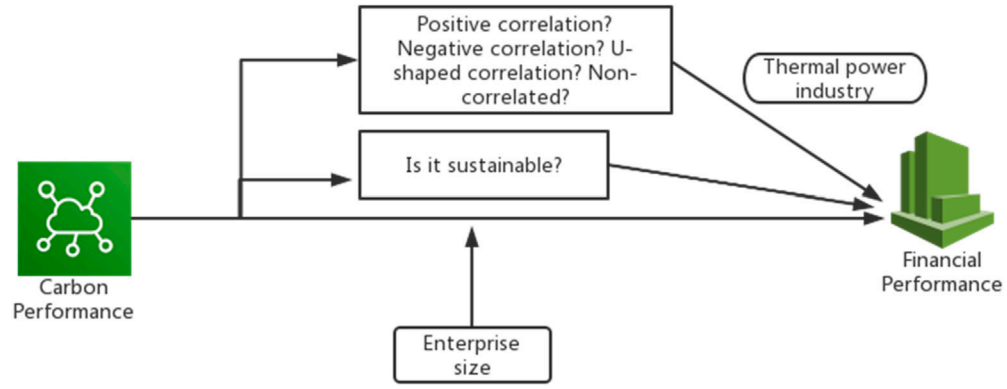
Under the background of "dual carbon," the power industry, as a pillar industry of the national economy, is ushering in changes. Based on the data of listed companies in the electric power production and supply industry from 2010 to 2020, this paper takes the operating income corresponding to each unit of carbon emission as the substitute variable of carbon performance (CP). After dimensionality reduction of 12 financial indicators through factor analysis, this paper establishes a comprehensive indicator of financial performance (FP), and establishes panel data to explore the relationship between CP and FP of electric power enterprises. To mitigate the endogeneity problem, 2SLS regression was performed using instrumental variables. The results show that CP has a positive and sustainable impact on the FP, which indicates that power enterprises need to pay attention to the long-term management of carbon emission reduction, so that the improvement of FP of enterprises can achieve sustainable development, which is in line with the expectations of Porter's hypothesis and stakeholder theory. In addition, firm size plays a negative moderating role in the relationship between CP and FP. The research results provide a path and basis for encouraging power enterprises to improve CP and help China achieve the goal of "dual carbon" as soon as possible.

KEYWORDS

dual carbon, carbon performance, financial performance, electric power enterprises, relationship

Highlights

- Relationship between Carbon and financial performance of electric power was explored.
- High carbon emission enterprises was identified and targeted.
- The size of enterprises is introduced as the adjusting variable.
- The measurement of financial performance indicators was improved.



GRAPHICAL ABSTRACT

1 Introduction

With the increasing global warming and environmental problems, climate change caused by carbon emissions has become an inevitable issue for economic growth and social development of various countries. The role of energy consumption is highly relevant to environmental protection and climate change. High levels of carbon monoxide emissions have become a serious global problem (Bekun et al., 2019). Globally, China is the second largest economy (Cheong, 2019) and the largest emitter of greenhouse gases (Koondhar et al., 2021). China's power industry is still thermal power generation as the main way of power generation, the annual carbon emissions of the power industry up to 3 billion tons, accounting for about 39% of the national carbon emissions, it can be seen that the power industry is reliant on China's carbon emissions. In addition, the first compliance cycle and online trading of the national unified carbon market in 2021 will include the power generation industry as the first batch of participants. As the main body of carbon emissions, whether enterprises can shift to low-carbon development mode or not is crucial to the realization of China's "dual carbon" goal. During the 14th Five-Year Plan period, the construction of ecological civilization in our country has turned to a strategic direction with energy saving and emission reduction as the focus, committed to carbon emission reduction and actively promoting global sustainable development (Peng et al., 2023). In accordance with the Paris Climate Change Agreement, China has rationally planned a "30–60 Target" of "Carbon Peak to Carbon Neutral." In the context of the "Dual Carbon" Goals, green finance of our country has been further developed and promoted (Fan et al., 2023).

With the continuous implementation of China's environmental protection policies, the rapid development of carbon emission trading and carbon trading market has a significant impact on the FP of enterprises at the micro level (Liu et al., 2021). In the process of implementing carbon reduction strategy to improve CP, enterprises will invest a lot of human, material and financial resources through the purchase of low-carbon equipment, research and development of carbon reduction technology, and introduction of carbon management talents, which will lead to the increase of enterprise operating costs. The impact of environmental performance on corporate performance, such as short-term costs or long-term benefits, has always been the focus of research (Eva Horváthová, 2012). Therefore, what impact the increased cost of implementing carbon emission reduction will have on the financial situation and enterprise development is an area that enterprises need to ponder over. Under the background of "dual carbon," Power industry of China puts forward higher requirements for energy conservation and emission reduction. Whether the economic benefits brought by the improvement of CP can make up for the new cost of carbon emission reduction will have a direct impact on the business strategy and business activities of power enterprises. Achieving the dual objectives of low carbon emission reduction and FP has become a common business issue (Yoo et al., 2020).

The power sector is a pillar of our economy, and reducing power-related carbon emissions is critical to achieving China's emission reduction targets, yet the relationship between carbon performance and financial performance in this sector is rarely discussed. Therefore, this paper takes thermal power enterprises as the research object. In order to evaluate enterprise FP more comprehensively and fully consider the characteristics of power enterprises represented by thermal power, 12 financial indicators are selected to construct FP evaluation system through structure factor analysis to fully reflect the FP level of enterprises, and panel data is established to explore the relationship between CP and FP of power enterprises. Exploring the relationship between CP and FP in the power industry is helpful for power enterprises to implement carbon emission reduction strategy and realize the goal of "dual carbon," and fill the research gap in related fields. At the same time, this paper introduces firm size to explore the relationship between the three. Although scholars have reached a consensus on the relationship between firm size and FP, the direction of the regulating effect of CP and FP curves cannot be determined theoretically, and further testing of large sample data is needed. Therefore, this paper further studies the regulating effect of firm size. It can not only provide empirical support for the research on the relationship between carbon performance and financial performance, but also provide certain reference value for power enterprises of different sizes in the process of implementing carbon emission reduction and pursuing profit maximization.

2 Literature review

2.1 "Dual carbon" and economic growth

Under the dual policy goals of carbon peaking (CEP) and industrial green transformation (IGT), China usually adopts top-down policy implementation and needs to build a better industrial green development plan (Zhou et al., 2022). A better understanding of the relationship between "dual carbon" and economic growth is conducive to industrial development and green development. From the perspective of mutual funds, Ji puts forward that China's green funds outperform other countries, and proposes that China can further achieve carbon neutrality while ensuring corporate performance and economic growth by introducing new carbon-friendly investment tools, promoting trading mechanisms, providing financial benefits, and reducing market friction (Ji et al., 2021). Starting from the Emissions Trading System (ETS), Zhang believes that in order to minimize carbon emissions, the government should improve the efficiency of supervision and formulate appropriate incentive strategies for excess emission reduction and punishment strategies for insufficient emission reduction. Reasonable free carbon quota ratio, lower technology emission reduction cost and higher carbon price can stimulate the enthusiasm of governments and enterprises to reduce emissions (Zhang et al., 2023). Hou, from the perspective of spatial characteristics and green finance, believes that the development of green finance will promote carbon neutral performance with regional consistency, and China needs to strengthen the green sustainable financial system, promote regional green finance, and improve the carbon neutral performance of green finance (Hou et al., 2023). From the perspective of the dual performance (DP) of environmental performance and corporate performance, Ding found that the incentive effect of green subsidies could make corporate performance reach the inflection point in advance and realize the synergistic growth of DP. The evolutionary game between the government and enterprises leads to the fluctuation of DP rising first, then decreasing, and finally rising. In addition, DP can develop cooperatively under collaborative governance to achieve the consistency of carbon decision-making behavior (Ding et al., 2022).

2.2 Measurement of CP

CP is also known as low CP, carbon reduction performance or carbon emission efficiency. The premise of measuring CP level is to obtain the corresponding carbon emission data. One is to use the carbon emission index disclosed in the mandatory report or voluntary report to measure the CP level of enterprises. For example, Ragini et al. (2019) studied the CP of American companies based on the carbon information in the CDP report. However, not all enterprises or regions are willing to participate in CDP projects, and China's carbon information disclosure system is not yet perfect, so there are not many enterprises that disclose carbon emission information, and the disclosure standards are different, resulting in the inability to directly obtain standardized and unified corporate carbon emission data. Therefore, most scholars use the main business income of enterprises and operating costs to estimate the proportion of carbon emissions of enterprises from the carbon emissions of industries to measure the level of CP (Busch and Lewandowski, 2016; Yan et al., 2022).

2.3 The relationship between CP and FP

Most scholars in the existing literature focus on the relationship between environmental performance and FP. However, with the deepening of research and the rise of the concepts of "carbon neutrality" and "carbon peaking," scholars have also begun to detail the relationship between CP, a branch of environmental performance, and FP. There are four views on the relationship between CP and FP.

Some scholars believe that CP is positively correlated with FP. Meng found that CP can significantly improve the FP of enterprises, and FP has a promotion effect on CP, and there is no lag effect (Meng et al., 2023). Timo Busch's meta-analysis results show that carbon emissions are inversely proportional to FP, indicating that good CP is usually positively correlated with excellent FP (Busch and Lewandowski, 2016). Manrique studied the impact of corporate environmental performance on corporate FP during the global financial crisis according to the economic development level of the country where the enterprise is located. They found that good environmental protection behaviors had a significant and positive impact on corporate FP in both developed and developing countries (Sergio and Martí-Ballester, 2017). Yan takes energy enterprises listed in China's A-shares as samples and finds that good CP and technological innovation in the energy industry have A positive impact on the FP of enterprises (Yan et al., 2022).

Some scholars believe that CP is negatively correlated with FP. Liu conducted an empirical study on the correlation between the environmental performance and financial performance of 16 heavily polluting industries in China, and found that the heavily polluting industries were negatively correlated with FP, and the improvement of environmental performance could not bring the overall improvement of FP (Liu et al., 2022). Liu investigated the impact of environmental responsibility performance on China's financial performance by constructing the evaluation index of corporate environmental responsibility. He found that corporate environmental responsibility has heterogeneity on FP, and in the central region of China, environmental responsibility is negatively correlated with FP (Liu et al., 2020). Tang conducted an empirical test with 293 Chinese heavily polluting enterprises as samples, and found that enterprises paying attention to environmental protection expenditure will bring good CP, but will have a significant negative impact on the current corporate FP (Tang et al., 2023).

Some scholars believe that the relationship between them is U-shaped. Ogunrinde integrates a process dimension based on an environmental management score with an outcome dimension represented by firms' carbon emissions intensity). By studying the relationship between corporate environmental performance and corporate financial performance, he found that there is a U-shaped relationship between the outcome dimension of corporate environmental performance in high-carbon intensive industries and FP, while the opposite is true for low-carbon intensive industries (Ogunrinde et al., 2020). Based on the provincial panel data of China's manufacturing industry from 2008 to 2019, Peng measured the relationship between carbon

intensity and green transformation ability in 30 provinces, and found that as more capital flows into pollution-dominated but profitable projects, carbon emission and financial performance show a U-shaped relationship (Peng and Guo, 2022). Starting from the core factors of enterprise profitability, Yang et al. found that there was a U-shaped relationship between carbon constraint and the profitability of large thermal power enterprises through theoretical analysis and empirical results. In the early stage, Yang et al. believed that the profitability of enterprises declined due to high research and development costs. Once this input becomes a heterogeneous resource that is difficult to replace, profitability will increase with the reduction of carbon emissions (Yang and Zhang, 2017).

Some scholars believe that there is no direct correlation between the two. Sun used general Bayesian networks to analyze the correlation between corporate environmental management activities, financial performance and financial characteristics, and found that there was no direct relationship between financial performance and corporate environmental management activities (Sun et al., 2018). Based on data from a database of industrial enterprises in China, Zhang determined the impact of companies' meeting energy efficiency targets on their FP. The results show that energy conservation has no significant impact on the FP of high-energy-consuming industries (Zhang et al., 2022). Dai analyzed the influence of carbon emission constraint on the performance of thermal power enterprises from both static and dynamic perspectives, and found that the influence of carbon emission constraint on enterprise performance is not absolute, and many factors such as technological innovation, management and operation will affect enterprise performance (Dai and Wang, 2020).

Domestic and foreign scholars have made rich achievements in studying the relationship between environmental performance and financial performance. They believe that there is a positive correlation between CP and FP in the literature, most of which take enterprises in developing countries as examples, and the selected enterprises are basically from the whole industry or the energy industry. The literature that considers the negative correlation between cp and fp is more focused on emerging countries or industries with serious pollution. For literatures with U-shaped or insignificant correlation, it may be affected by sample selection, such as industry and regional heterogeneity; It is also affected by the internal factors of the enterprise, such as the technological innovation of the enterprise, the mode of operation and so on.

However, the research on the relationship between carbon performance and financial performance is relatively scarce. By combing and comparing the literature, the following shortcomings are drawn: 1) The academic community has not reached a unified conclusion on the relationship between the two. There are heterogeneous and complex interactions between the two structures in general. Selection of different research periods, research perspectives and indicators may lead to different research conclusions (Hoppe and Guenther, 2014; Markus et al., 2018). Most scholars disagree on whether the relationship between carbon performance and financial performance is positive or negative. A few scholars propose that the relationship between the two is inversely "U" shaped correlation and non-correlation. 2) The selection of carbon performance evaluation methods and indicators is highly subjective. There is no unified standard for measuring carbon performance in academic circles. Some scholars choose a single variable to measure carbon performance by absolute or relative value, while others choose multiple environmental indicators and financial indicators to jointly build a carbon performance evaluation system.

To sum up, many literatures only discuss the single influence of CP on FP, ignoring other factors that affect the relationship between the two. In particular, few studies introduce the relationship between the two as a moderating variable, few literatures comprehensively examine the mechanism of action of the three, and few studies explore the relationship between CP and FP with domestic micro-enterprises as research objects. Starting from the shortcomings of the research on the relationship between the two, this paper selects the power industry as the research object, adopts a more comprehensive performance evaluation index and considers the regulating effect of enterprise scale on the relationship between the two. Therefore, the research on the relationship between carbon performance and financial performance is more comprehensive and targeted.

3 Theoretical analysis and research hypothesis

Although under the influence of environmental regulations, high-carbon enterprises inevitably need to increase the corresponding cost to meet the requirements of environmental policies. However, Porter's hypothesis holds that appropriate environmental regulations can improve the FP of enterprises and ultimately offset the costs of carbon reduction measures. For example, enterprises can reduce unnecessary energy consumption and improve their CP by introducing low-carbon environmental protection equipment and researching and developing low-carbon technologies (Gao and Zhou, 2015), which can not only relieve the pressure of legality and avoid environmental penalties, but also get the government's policy support in terms of tax incentives and environmental protection subsidies, so as to make up for the incremental cost of investment to a certain extent.

Secondly, stakeholder theory holds that enterprises need to achieve a balance between economic interests and various stakeholders when implementing strategic decisions. With the improvement of low-carbon awareness in all sectors of society, especially after the "dual carbon" goal was proposed, carbon information has gradually become a non-financial indicator concerned by stakeholders because it is closely related to the sustainable development of enterprises. Stakeholders need to be involved in carbon reduction activities to achieve carbon peaking and carbon neutrality. Wang pointed out that five stakeholders affecting carbon emission reduction intensity are listed in descending order as follows: manufacturing enterprises, government, energy supply industry, research and development organizations, and financial institutions (Wang et al., 2022). The pressure on enterprises to reduce carbon emissions is also increasing under the influence of low-carbon requirements from stakeholders such as governments and financial institutions. Companies need to take reasonable carbon reduction measures and actions to meet stakeholder requirements. If an enterprise's carbon emission

reduction measures are ineffective and its CP level is low, it will send a negative signal to stakeholders and thus make the enterprise face public opinion or substantial pressure from stakeholders. By implementing carbon emission reduction strategies and actively improving CP, enterprises can build their green reputation, which reflects their competitive advantages. This green reputation not only helps reduce business risks, but also helps enterprises obtain more favorable business conditions in negotiations with various stakeholders. Meanwhile, the improvement of CP also provides opportunities for enterprises to expand market share and obtain new resources. This will further increase the profits of enterprises (Baah et al., 2019). In addition, carbon disclosure is a form of enterprise's positive concern for the environment, which is positively responded by the market and is the basis for investors to evaluate the sustainability of the company. Therefore, carbon disclosure has a positive and significant impact on enterprise value. Enterprises with good CP are more motivated to disclose carbon information to external stakeholders, so as to reduce the degree of information asymmetry and reduce the cost of capital, and then integrate carbon information into stock price and improve FP (Hardiyansah et al., 2021). Based on the above analysis, this paper proposes the following hypotheses:

H1: CP has a positive impact on FP.

To achieve the goal of "dual carbon" is a long-term task. As the main body of carbon emissions, enterprises need to promote the green upgrading of existing facilities, accelerate the research and development and application of advanced and applicable technologies, strengthen innovation capacity, and carry out green and low-carbon transformation. The dividend brought by improving CP may make enterprises increase their investment in carbon emission reduction. However, based on the principle of diminishing marginal benefit, increasing the input of production factors will increase the output, but after the input exceeds a certain degree, the output will decrease, and the low sales ability will result to the loss of enterprise interests. For example, in the automotive industry, there is a strong and persistent negative correlation between carbon emissions and FP, which is associated with lower return on sales and lower capital efficiency for high-emission companies (Palea and Cristina, 2022). Therefore, after the investment in carbon emission reduction improves the CP to a certain extent, the phenomenon of diminishing marginal benefits may appear, thus damaging the financial interests of enterprises and hitting the enthusiasm of enterprises to achieve the "dual carbon" goal. Based on the above analysis, this paper proposes the following hypotheses:

H2: The positive effect of CP on FP is not sustainable.

In the study of the relationship between CP and FP, enterprise size is mostly used as the control variable in variable design. While increased capital expenditures by companies to improve their CP will increase their operating costs to some extent, the impact of these additional costs may not be the same for companies of different sizes. Under normal circumstances, smaller enterprises have lower access to resources and information than larger enterprises, resulting in greater operational risks and external pressure. Improving CP through environmental governance can alleviate agency problems to a certain extent and improve corporate image to gain market recognition or attract external investment, thus improving profitability. Large scale enterprises are in a leading position in the industry, and their rich financing channels and resources make them less motivated to improve environmental governance to improve profitability. The size of the enterprise also has a certain impact on the management structure and the formulation of the enterprise strategy. Larger enterprises emit more pollutants and have more stakeholders, so they are subject to higher supervision by the government and society. In the process of operation, they not only need to consider profit, but also need to bear more environmental and social responsibilities, which may also lead to inefficient investment. According to Deng Xiang's research, environmental regulation is negatively correlated with the FP of enterprises, and the sensitivity of state-owned enterprises to environmental regulation is higher than that of non-state-owned enterprises (Deng and Li, 2020). Therefore, the following hypothesis is proposed:

H3: Firm size plays a negative moderating role in the relationship between CP and FP.

4 Research design

4.1 Sample selection and data source

This paper selects the data of thermal power enterprises listed on Shanghai and Shenzhen A-shares from 2011 to 2020. The reason is that thermal power generation is still the main power generation mode in China's power industry and thermal power generation is an important source of carbon emissions in the power industry. Therefore, thermal power enterprises will be more representative and comparable when studying the relationship between CP and FP of power enterprises. Up to now, the China Energy Statistical Yearbook has not updated the industry energy consumption data after 2020, so the observation period is until 2020. According to the 2012 edition of the industry classification of the CSRC, select such enterprises and screen them, the process is as follows: 1) Eliminate listed enterprises, ST, *ST, and main business changes after 2011; 2) Eliminate listed enterprises with abnormal data, missing data, and delisting. A total of 29 sample enterprises and 290 sample data were obtained. The financial data are mainly from the CSMAR database, and other data are mainly from the China Energy Statistical Yearbook. In order to reduce the Influence of outliers, this paper carries out 1%–99% indent processing for all continuous variables, and mainly uses Spss26.0 and Stata16.0 software for data processing.

4.2 Variable definition

4.2.1 Explanatory variables

The direct purpose of enterprises to improve their CP level is to reduce carbon emissions. Using carbon emissions to measure CP level not only conforms to the definition of performance but also reflects the carbon emission reduction results of enterprises. Therefore, this paper intends to draw on the method proposed by Zhao, divide the main business income of an enterprise by the carbon emission of an enterprise, and take the logarithm as the CP index of an enterprise (Zhao et al., 2021). However, because Chin's carbon information disclosure system is not yet perfect, there are not many enterprises that disclose carbon emission information, and the disclosure standards of different enterprises are not uniform, and the

TABLE 1 Carbon emission coefficients of various energy sources.

Energy type	Reference coefficient of standard coal	Carbon emission coefficient (10^4t/10^4tce)
Raw coal	0.7143	0.7559
Coke	0.9714	0.8550
Crude oil	1.4286	0.5857
Gasoline	1.4714	0.5538
kerosene	1.4571	0.5714
Diesel oil	1.4571	0.5921
Fuel oil	1.4286	0.6185
Natural gas	1.3300	0.4483

TABLE 2 Financial performance evaluation system.

Primary index	Secondary index	Code
Operational capacity	Accounts receivable turnover rate	X_1
	Turnover of total assets	X_2
Profitability	Return on assets	X_3
	Return on equity	X_4
	Operating profit margin	X_5
	Profit rate of cost expense	X_6
	Basic earnings per share	X_7
Solvency	Current ratio	X_8
	Quick ratio	X_9
	Asset-liability ratio	X_{10}
Development ability	Growth rate of net assets	X_{11}
	Revenue growth rate	X_{12}

carbon emission data of Chinese enterprises can not be directly obtained, so the carbon emission of enterprises is estimated by the carbon emission of the industry with the help of business costs.

Specific calculation steps: (1) Multiply the various energy consumption of the power industry published in the China Energy Statistical Yearbook with the corresponding reference coefficient and carbon emission coefficient to obtain the carbon emission of the industry. (As shown in Table 1) ② Enterprise carbon emission = enterprise main business cost/(industry main cost)× industry carbon emission. ③ Corporate CP cp = Ln(corporate main business income/corporate carbon emissions).

4.2.2 Explained variable

Scholars usually choose a single indicator to measure FP, such as ROA or TobinQ value (Zhao et al., 2021; Fortune, 2018; Meng et al., 2023), but this paper believes that only a single indicator to measure the FP of enterprises cannot fully reflect the financial situation of enterprises. In order to evaluate the FP of enterprises more comprehensively and fully consider the characteristics of power enterprises represented by thermal power, this paper intends to select 12 financial indicators to build a FP evaluation system through structure factor analysis, so as to fully reflect the FP level of enterprises (Table 2).

4.2.3 Moderating variable

The difference of enterprise scale will affect the resource acquisition ability and accumulation ability of enterprises. Large-scale enterprises have relatively rich capital accumulation and strong anti-risk ability. And its importance to the market economy is higher, more concerned by the state and society. Therefore, large-scale enterprises will pay more attention to corporate image and social responsibility, increase their investment in environmental protection, and have high enthusiasm in implementing carbon emission reduction strategies. Therefore, the difference of enterprise scale has a certain impact on CP and FP. In this paper, the firm size is expressed using the natural logarithm of total assets at the end of the period.

4.2.4 Control variable

This paper mainly explores the relationship between CP and FP. The research object focuses on the internal power enterprises, and the difference of external environmental impact is relatively small. By referring to the research of relevant scholars, the size of enterprises, listing years, financial leverage and ownership concentration are selected as control variables. The relevant variables and their definitions are shown in Table 3.

4.3 Research model design

In order to test the relationship between CP and FP, the following model is constructed to verify hypothesis 1 (Eq. 1):

$$fPit = \alpha 1 + \beta 1cPit + \beta 2AGEit + \beta 3IDRit + \beta 4LEVit + \beta 5oCit + \gamma it \quad (1)$$

In order to test whether CP is sustainable to FP, the following model is constructed to verify hypothesis 2 (Eq. 2):

TABLE 3 Variable selection and definition.

Variable type	Variable name	Symbol	Variable definition
Explained variable	Financial performance	FP	The factor analysis method is used to reduce the dimension of the selected indicators and evaluate the financial performance comprehensively
Explanatory variable	Carbon performance	CP	Ln (The main business income of the enterprise/Corporate carbon emission)
Regulating variable	Enterprise scale	SIZE	Ln (Total assets at year-end)
Control variable	Listed Years	AGE	Ln (Reporting year-Listing year)
	Board independence	IDR	Number of independent directors/Total number of directors
	Financial leverage	LEV	Asset-liability ratio
	Ownership concentration	OC	Number of shares held by the largest shareholder/Total capital stock of enterprise
	Year	Year	Dummy variable

$$fPi,t+n=\alpha 1+\beta 1cPit+\beta 2AGEi,t+n+\beta 3IDRi,t+n+\beta 4LEVi,t+n+\beta 5oCi,t+n+\gamma it \quad (2)$$

Where n = 1,2,... . If n = 1, it represents the impact of CP in the current period on FP in the lagging period.

In order to test the moderating effect of firm size on the relationship between CP and FP, the cross-multiplication term of CP and firm size is introduced(inter = cPit*SIZEit). Construct the following model to verify hypothesis 3 (Eq. 3):

$$fPit=\alpha 1+\beta 1cPit+\beta 2AGEit+\beta 3IDRit+\beta 4LEVit+\beta 5oCit+\beta 6SIZEit+\beta 7interit+\gamma it \quad (3)$$

5 Empirical test and result analysis

5.1 Descriptive statistics

This paper uses Stata16.0 software to conduct descriptive statistics on the sample data. The descriptive statistical results of all variables are shown in Table 4. The maximum value of FP (FP) is 1.592 and the minimum value is −1.950, indicating that there is a large gap in the FP of thermal power sample enterprises. The maximum value of CP (CP) is 7.401, and the minimum value is 6.159. There is still a gap between some enterprises and the average value of the industry, and the carbon emission reduction efforts of enterprises are different. Some enterprises have low carbon emission reduction awareness and insufficient carbon emission control efforts, and there is still a large room for improvement.

The maximum value of enterprise S″ze i′ 26.81, the minimum value is 20.99, the mean value is 24.20, and the standard deviation is 0.243, indicating that the overall scale of the sample enterprises is large, and the size difference among enterprises is small, mainly because the fixed assets of electric power enterprises account for a high proportion of total assets. In this paper, the natural logarithm of total assets is adopted to measure enterprise size. The mean value of financial leverage (LEV) is 0.635, the standard deviation is 0.147, and the maximum is 0.937. The overall leverage level of the industry remains at a reasonable level, but the leverage of individual enterprises is too high and needs to be adjusted in a timely manner. For listing years (Age), this variable is measured by taking the natural logarithm of the difference between the reporting year and the listing year. The maximum value is 3.296 and the average value is 2.787, indicating that the overall development of the sample enterprises is relatively mature. The maximum value of ownership concentration (OC) is 0.834 and the average value is 0.437, indicating that the overall ownership of listed thermal power companies is relatively concentrated. The maximum value of the independence of the Board of directors (IDR) is 0.356 on average, 0.6 on maximum, and 0.231 on minimum, indicating that there are still enterprises that fail to meet the Company La's requirement that the number of independent directors shall not be less than one third of the board members.

As shown in Figure 1, the average value of CP has remained stable and increased from 2011 to 2020. Especially after the pilot carbon trading policy in 2013, power enterprise' awareness of carbon emission control has been strengthened year by year, and CP level has also maintained a good development trend.

5.2 Correlation analysis

In order to understand the correlation between variables and their significance level, correlation analysis was carried out on each variable, as shown in Table 5. It can be seen from the table that the correlation coefficient between the FP (FP) of the explained variable and the CP (CP) of the explained variable is 0.263 and positively correlated at the significance level of 1%. It indicates that the improvement of CP (CP) will contribute to the improvement of FP (FP). A preliminary proof is provided for hypothesis 1.

In this paper, VIF test was conducted on whether there was multicollinearity between variables. The results were shown in Table 6. The maximum value of variance inflation factor was 1.40, and the variance inflation factor of each variable was much lower than 10, indicating that there was no multicollinearity between variables and regression analysis could be conducted.

TABLE 4 Descriptive statistical results of all variables.

Variable	N	Maximum value	Minimum value	Mean value	Standard deviation
FP	290	1.592	−1.950	0	0.567
CP	290	7.401	6.159	6.625	0.243
Size	290	26.81	20.99	24.20	1.205
OC	290	0.834	0.136	0.437	0.152
Age	290	3.296	1.609	2.787	0.323
IDR	290	0.600	0.231	0.356	0.0680
LEV	290	0.937	0.172	0.635	0.147

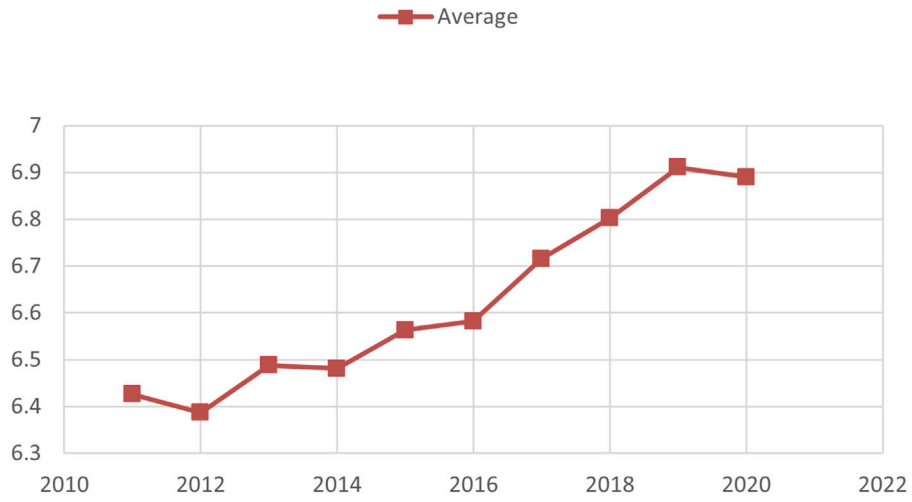


FIGURE 1
Changes in carbon performance trends.

TABLE 5 Correlation analysis.

	FP	CP	Size	OC	Age	IDR	LEV
FP	1						
CP	0.263***	1					
Size	−0.116**	0.210***	1				
OC	0.214***	−0.194***	0.094	1			
Age	0.121**	0.297***	0.028	0.287***	1		
IDR	0.139**	−0.216***	−0.217***	0.233***	−0.036	1	
LEV	−0.395***	−0.05	0.283***	−0.142**	−0.328***	−0.102*	1

Note: ***, ** and * are statistically significant at 1%, 5% and 10% respectively.

5.3 Multiple regression analysis

Before the regression analysis, F-test and Hausmann test are required to select a model suitable for the study of the relationship between CP and FP of thermal power enterprise' balance panel data from 2011 to 2020. In the F-test comparing the mixed model and the fixed effect model, the *p*-value is 0, indicating that the null hypothesis is rejected, that is, the fixed effect model is superior to the mixed model. In the Hausmann test comparing the fixed effects and random effects models, the *p*-value is 0, that is, the fixed effects model should be chosen over the random effects model. Based on the above test results, the fixed effect model is more suitable for the study of this paper.

TABLE 6 Multicollinearity test.

	CP	Size	OC	Age	IDR	LEV
VIF	1.31	1.25	1.32	1.40	1.15	1.25
1/VIF	0.766	0.802	0.758	0.715	0.868	0.798

TABLE 7 Regression analysis of the relationship between CP and FP.

Variable	FP
CP	1.753***
	(10.56)
OC	0.750***
	(3.90)
Age	0.108
	(0.97)
IDR	0.711*
	(1.75)
LEV	−1.563***
	(-8.25)
Constant	−11.058***
	(−9.43)
Observations	290
R-squared	0.424
Year	YES
Adj_R2	0.395
Prob>F	0
F-test	14.483

In order to verify that H1: CP has a positive impact on FP, regression analysis is performed on model (1), and the results are shown in Table 7. The R^2 is 0.424 and the adjusted R^2 is 0.395, indicating that the model has a good overall fitting effect. CP (CP) and FP (FP) are significantly positive at the 1% level. It shows that the improvement of CP level will contribute to the improvement of FP. H1 is verified. It shows that power enterprises attach a high degree of importance to carbon emission reduction, and their investment in carbon emission reduction wins the favor of stakeholders, enhances the flexibility of enterprises, and makes it easier to translate carbon emission reduction achievements into FP. Therefore, CP has a positive impact on FP. In order to verify H2: the positive impact of CP on FP is not sustainable. Regression analysis was performed on model (2), and the results were shown in Table 8. On the basis of model (1), regression analysis was conducted on the CP of the current period and the FP of the period lagging phase 1 and phase 2 to test whether the positive impact of CP on FP was sustained. The results showed that the regression coefficient of CP of the current period on the FP of the period lagging phase 1 and phase 2 was positive, and both passed the significance level test of 1%. The result of regression analysis is contrary to H2, that is, the positive impact of CP on FP is persistent. It shows that the investment in carbon emission reduction of power enterprises makes CP have a positive effect on FP when CP is increased to a certain extent, but this effect shows a diminishing marginal effect. Therefore, it is necessary to attach importance to the long-term management of carbon emission reduction, and enterprises need to allocate resources reasonably according to their own conditions, so as to achieve sustainable development of FP improvement of enterprises.

In order to test the regulating effect of firm size on the relationship between CP and FP, the interaction term (inter) between CP and firm size was introduced for regression analysis. The results are shown in Table 9. First, it can be seen from the main effect analysis of model (1) that the regression coefficient of CP on FP is 1.753, which passes the significance level test of 1%. In other words, CP has a significant positive impact on FP. Based on this, the adjustment effect analysis of enterprise size is conducted. According to model (2), it can be seen that the regression coefficient of the interaction term (inter) between enterprise size and CP on FP is −0.248 and passes the significance test of 5%, so enterprise size belongs to the interference adjustment effect, which proves hypothesis 3 is valid. That is, enterprise size negatively regulates the positive impact of CP and FP.

In addition, the adjusted R^2 in model 1 is 0.395, and the adjusted R^2 in model 2 is 0.405, which increases somewhat, further indicating that the introduction of adjustment variables is reasonable.

In order to more clearly show the adjustment effect of enterprise size, Excel table is used to draw the adjustment effect of enterprise size, as shown in Figure 2.

5.4 Robustness test

5.4.1 Control of endogenous problems

Considering that there may be mutual influence between CP and FP, in order to solve the potential endogenous problem, the method proposed by Yan Huahong was used to study the lag of explanatory variable (CP) one stage as the instrumental variable, and 2SLS regression was carried out (Yan et al., 2019). The results are shown in Table 10. The instrumental variable passed the under-recognition test and the weak instrumental variable test. In addition, it can be seen from the results of the first stage that L.cp and cp are significantly positively correlated at the level of 1%, which indicates the rationality of the instrumental variables selected in this paper. As can be seen from the regression results of the second stage, IV-2SLS is basically consistent with the previous regression results, and the promoting effect of CP on FP is significantly positive, which indicates that the endogenous problem is controlled.

5.4.2 Treatment of robustness problem

In order to verify the accuracy of the above model and the results of regression analysis, this paper intends to test the robustness of the model, replace the original FP indicator FP with ROE and keep other variables unchanged, and conduct a regression analysis on the hypothesis again. The results are shown in Table 11. The regression coefficient between carbon performance (CP) and financial performance (ROE) is 0.242. The T statistic value is 9.21, which further proves that there is a significant positive correlation between CP and FP through the

TABLE 8 Regression results.

Variable	FP	Lagged variable FP	Two-period lagged FP
CP	1.753***	1.324***	0.988***
	(10.56)	(6.95)	(4.73)
OC	0.750***	0.875***	0.924***
	(3.90)	(3.94)	(3.75)
Age	0.108	0.003	−0.043
	(0.97)	(0.02)	(-0.32)
IDR	0.711*	0.624	0.402
	(1.75)	(1.33)	(0.77)
LEV	−1.563***	−1.646***	−1.631***
	(−8.25)	(−7.47)	(−6.65)
Constant	−11.058***	−7.95***	−5.736***
	(−9.43)	(−6.06)	(−3.97)
Observations	290	261	232
R-squared	0.424	0.326	0.268
Year	YES	YES	YES
Adj_R2	0.395	0.290	0.227
Prob>F	0	0	0
F-test	14.483	9.172	6.667

Note: ***, ** and * are significant at the level of 1%, 5% and 10% respectively, and the t statistic is in parentheses, the same below.

significance level test of 1%. At the same time, the replaced FP indicators are delayed to test whether there is continuity between CP and FP in the current period. Through re-regression analysis, CP can still effectively improve the FP of the lag phase 1 and lag phase 2. The regression coefficient between the current CP and the ROE one period behind is 0.202, and the T-value is 6.8, passing the 1% significance level. The regression coefficient between CP in the current period and ROE in the second lagging period is 0.161, and the T-value is 4.78, which also passes the significance test at the 1% level, further proving that the positive impact of CP on FP is sustained.

The robustness test of hypothesis 3 is conducted, and the results are shown in Table 12. The regression coefficient of the interaction term (inter) between CP and firm size is −0.057 and passes the significance test of 1%, which further proves the validity of hypothesis 3.

6 Discussion

The academic community has not yet formed a unified view on the relationship between CP and FP. Traditional economists believe that environmental regulations will lead to the company that causes environmental pollution to bear the corresponding environmental costs, which will lead to the increase of enterprise operating costs and further affect the FP of enterprises. However, scholars based on Porte's hypothesis and stakeholder theory believe that appropriate environmental regulations can stimulate enterprises to carry out ecological innovation, and the economic benefits obtained through innovation can offset the new environmental costs, thus forming competitive advantages in the market and obtaining good economic benefits. A large number of studies by Sun Zhao Yong and Yan also show that improving corporate social responsibility capability is an effective way to promote FP, and good CP is usually positively correlated with excellent FP(Sun and Park, 2023; Yan et al., 2019).

Carbon emissions from Chin's power sector account for about one-seventh of global carbon dioxide emissions and half of Chin's carbon dioxide emissions (Jiang et al., 2018). Reducing power-related carbon emissions is critical to achieving Chin's emission reduction targets (Wei et al., 2017). The governmen's strict environmental regulations put forward higher "low-carbo" requirements for high-carbon emission enterprises such as electric power enterprises, but by implementing "carbon emission reductio," electric power enterprises can improve the utilization rate of resources, avoid environmental penalties, and enjoy government subsidies and tax incentives. In addition, due to the particularity of the industry, electric power enterprises involve more stakeholders, and the pressure caused by stakeholders in the process of reducing carbon emissions becomes the driving force for enterprises to make environmental commitments, improve CP, and achieve the goal of "dual carbo" (Silva et al., 2013). While fulfilling their social responsibilities and improving CP, electric power enterprises can also improve CP. By integrating green resources and improving the green attributes of products, the company can optimize its own image to win the favor of more stakeholders, increase the loyalty and

TABLE 9 Regression results of adjustment effect.

Variable	Model (1)	Model (2)
C_CP	1.753***	1.767***
	(10.56)	(10.70)
C_Size		−0.28
		(−1.17)
Inter		−0.248**
		(-2.44)
OC	0.750***	0.872***
	(3.90)	(4.37)
Age	0.108	0.112
	(0.97)	(1.00)
IDR	0.711*	0.542
	(1.75)	(1.31)
LEV	−1.563***	−1.474***
	(−8.25)	(−7.41)
Constant	−11.058***	−11.203***
	(−9.43)	(−9.60)
Observations	290	
R-squared	0.438	
Year	YES	
Adj_R^2	0.395	0.405
Prob>F	0	0
F-test	14.483	13.315

satisfaction of customers with green preferences to products, expand the market share, improve the relationship with government regulators, improve the value of enterprises, and play a positive role in FP. Therefore, enterprise managers need to pay attention to the long-term management of carbon emission reduction, so as to improve the FP of enterprises for sustainable development. The combination of carbon reduction strategy and business strategy to achieve a win-win situation of environmental and economic benefits.

Chin's inter-provincial trade leads to the increase of power-related carbon emissions and the flow of carbon emissions (Wei et al., 2020). The electric power industry, as the first industry incorporated into the carbon emission rights trading system in China, internalizes the external cost of carbon emissions of electric power enterprises under the influence of carbon emission rights trading policy. Those who exceed the limit buy carbon credits through carbon trading or pay environmental penalties. Yuan believed that the adoption of emission reduction technology could effectively reduce the impact of carbon constraints on output, reduce emissions and purchase carbon emission rights, and realize environmental and economic dividends (Yuan et al., 2022). Enterprises reduce carbon emissions through technological innovation, such as purchasing or updating production equipment. By selling the excess carbon emission rights in the secondary market, they can make up for the environmental costs incurred by purchasing or updating equipment. It can be seen that Porte's hypothesis and stakeholder theory have been confirmed in the research on the relationship between CP and FP of electric power enterprises in China.

In addition, this paper adds and validates a new important factor in exploring the relationship between the two-- firm size. Although environmental investment in order to improve environmental performance will increase the operating costs of enterprises to some extent, the impact of such cost increase on companies of different sizes is different. Although scholars have reached a consensus on the relationship between enterprise size and FP, when it comes to the directionality issue, However, there are two different views: diseconomies of scale or diminishing returns to scale and increasing economies of scale or returns to scale.

However, the existence of economies of scale has forced scholars to reflect on the positive relationship between enterprise scale and efficiency, that is, the possibility of increasing returns to scale. Gun JeaYu and Andries believe that enterprise scale has a significant moderating effect on the relationship between FP and environmental performance (Gun et al., 2016; Andries and Stephan, 2019). However, the larger the enterprise scale, the more stakeholders will be involved in its production and operation, and the more environmental and social responsibilities must be considered in the process of business decision-making, which may lead to more resources being invested in projects that cannot bring economic benefits to the enterprise in the short term. The problem of inefficient investment leads to a decline in resource utilization and offsets the positive impact of CP on FP to a certain extent. Zhang took 11909 micro-industrial enterprises in Anhui Province, China as research objects, and found that the enterprises that improved performance were mainly low-energy enterprises and small enterprises. In contrast, most of the enterprises with declining performance are high energy-consuming enterprises and large enterprises (Zhang et al., 2018).

It can be seen that although the existence of the regulating effect of enterprise size on the relationship between CP and FP curve is theoretically established, the direction of this regulating effect cannot be determined theoretically, and further large-scale sample data testing is needed. Therefore, this paper further studies the regulating effect of enterprise size.

7 Conclusion and policy recommendations

7.1 Conclusion

This paper takes 29 A-share listed power enterprises as samples, selects 2011–2020 as the research interval, explores the relationship between carbon performance and financial performance of power enterprises under the background of "dual carbon," and draws the following conclusions:

(1) Carbon performance has a positive impact on financial performance. The regression results show that the regression coefficient of carbon performance and financial performance is positive and passes the

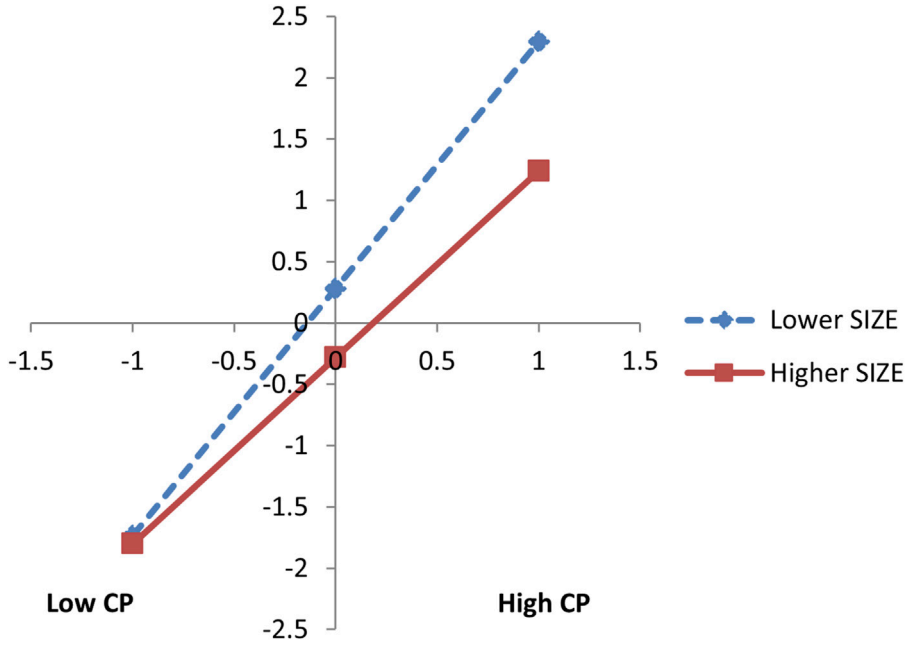


FIGURE 2
Influence of firm size on the relationship between carbon-based performance and financial performance.

significance test of 1%, and passes the robustness test. Enterprises achieve carbon emission reduction through carbon management to improve the level of carbon performance is conducive to improving financial performance. A high level of carbon performance is a manifestation of an enterprise's active commitment to social responsibility and adherence to the path of green and low-carbon development, which can send positive signals to the market and enhance the green image of an enterprise. At the same time, although the improvement of carbon performance will bring about a surge in costs in the short term, it is conducive to reducing production costs in the long run.

(2) The positive impact of carbon performance on financial performance is sustained. The regression analysis of carbon performance in the current period and financial performance by lagging one and two periods shows that carbon performance in the current period has continuity to financial performance. Enterprises rationally arrange resources and management plans and incorporate carbon emission reduction strategies into their long-term strategic development plans. By reducing carbon pollution and green production to change the extensive economic development mode, enterprises can improve their reputation, shape their good image, attract the participation of potential investors, increase inestimable intangible benefits, and improve their performance.

(3) Firm size plays a negative moderating role in the relationship between carbon performance and financial performance. The larger the scale of the enterprise, the more stakeholders involved in its production and operation, the more environmental and social responsibilities must be considered in the process of business decision-making, and more resources may be invested in projects that cannot bring economic benefits to the enterprise in the short term. The problem of inefficient investment leads to the decrease of resource utilization and offsets the positive impact of carbon performance on financial performance to a certain extent.

7.2 Policy recommendations

7.2.1 Government level

7.2.1.1 Improve the carbon information disclosure system and strengthen supervision

"Carbon information disclosure" is a way to obtain the "carbon performance" of enterprises. Since CP has a positive effect on FP, and this effect is persistent, the disclosure system of carbon information needs to be improved. Carbon information is also a component of accounting information. The Accounting Standards for Business Enterprises can clearly specify the time, way and the content of carbon information disclosure, establish responsibility investigation and punishment system, promote enterprises to disclose carbon information more fully, and formulate unified and standardized statistical accounting methods for carbon emissions. Clear accounting caliber, emission factors and other information makes carbon information disclosure more standardized and standardized. It is also necessary to integrate carbon information supervision resources and build a carbon audit supervision system that combines government audit supervision, enterprise internal control audit and third-party independent audit represented by professional service institutions. Establish and improve the mechanism for carbon

TABLE 10 Results of two-stage regression of instrumental variables.

Variables	First stage	Second stage
	cp	FP
cp		3.372***
		(5.06)
Size	0.059***	−0.314**
	(2.63)	(-2.01)
OC	0.205**	0.911
	(2.30)	(1.53)
Age	−0.042	1.233**
	(−0.52)	(2.37)
IDR	0.038	0.254
	(0.52)	(0.56)
LEV	0.005	−0.111
	(0.07)	(-0.28)
L.cp	0.512***	
	(9.41)	
Year	YES	YES
R-squared	0.926	0.396
LM statistic	67.003***	
Cragg-Donald Wald F	88.526	
10% maximal IV size	16.380	

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$, t-statistics in parentheses.

TABLE 11 Robustness test results.

Variable	ROE	Lagged variable	Two-period lagged
CP	0.242***	0.202***	0.161***
	(9.21)	(6.80)	(4.78)
OC	0.146***	0.163***	0.174***
	(4.80)	(4.71)	(4.39)
Age	−0.012	−0.027	−0.036*
	(-0.70)	(−1.38)	(−1.66)
IDR	−0.029	−0.027	−0.049
	(−0.45)	(−0.37)	(−0.58)
LEV	−0.118***	−0.141***	−0.149***
	(−3.93)	(-4.09)	(-3.79)
Constant	−1.478***	−1.172***	−0.891***
	(−7.98)	(−5.72)	(−3.84)
Observations	290	261	232
R-squared	0.466	0.423	0.385
Year	YES	YES	YES
Adj_R2	0.439	0.392	0.351
Prob>F	0	0	0
F-test	17.129	13.912	11.416

information to be compatible with the full coverage of the audit, and require enterprises subject to carbon emission control to disclose the audited carbon information together with their annual financial report or ESG report.

7.2.1.2 Strengthen the attention and incentive system for small and medium-sized enterprises

Since enterprise size plays a negative regulating role in the relationship between CP and FP, small and medium-sized enterprises need to pay more financial costs than large enterprises while ensuring good carbon performance. The government should improve the incentive system for carbon emission reduction. For example, for enterprises that actively adjust the energy structure and achieve good carbon emission reduction results, tax relief can be granted according to corresponding standards. On this basis, more tax incentives or publicity can be given to small and medium-sized enterprises that actively respond to the policy and have good carbon emission reduction effects. To realize the positive transformation between CP and FP under the premise of guaranteeing the interests of small and medium-sized enterprises.

7.2.2 Industry level

Guided by industry associations, technical and operational management exchanges and cooperation among power enterprises will be strengthened by organizing industry summits and other forms. For a series of “dual carbon” policies, do a good job of collecting difficulties and suggestions from power enterprises, especially pay attention to the difficulties put forward by small and medium-sized enterprises, carry out forward-looking research in combination with the actual situation of the industry and give feedback to the government regulatory authorities. The association awards power enterprises with outstanding carbon emission reduction and financial performance, and acts as an intermediary to promote exchanges and learning among enterprises, ensuring that small and medium-sized enterprises can get exchanges and research opportunities.

7.2.3 Enterprise level

7.2.3.1 Pay attention to carbon management and develop a top-level plan for its long-term management

Power enterprises need to base on the “dual carbo” era background, in the medium and the long term development strategy of carbon reduction, pay attention to the development trend of carbon emissions and the impact of “dual carbo” on the development of enterprises. Enterprises should clarify low-

TABLE 12 Robustness test of regulatory effects.

Variable	ROE
C_CP	0.567***
	(8.60)
C_Size	0.028
	(−0.80)
Inter	−0.057***
	(−3.36)
OC	0.098
	(1.35)
Age	0.126
	(1.53)
IDR	−0.032
	(−0.61)
LEV	0.057
	(0.69)
Constant	−0.263
	(-1.13)
Observations	290
R-squared	0.545
Year	YES
Adj_R^2	0.519
Prob>F	0
F-test	50.56

carbon development goals, including reducing carbon emissions, improving energy efficiency, and adopting renewable energy. These goals should be measurable, attainable and sustainable to ensure the effectiveness of long-term planning. We can learn from the development strategies of large energy groups in Europe and the United States, set up a "carbon strategy management departmen" to establish a sound management system for carbon emission reduction, promote carbon budget management, let all departments participate in the formulation and modification of carbon budget, combine emission reduction targets with business plans in light of the actual situation of production and operation of enterprises, and change the previous passive work mode of energy conservation and environmental protection. The implementation of carbon cost management, the carbon emission reduction cost of each production link into the cost accounting, the manager proposed the corresponding refined cost management plan, and implemented in the whole process of production. For traditional thermal power enterprises, it is more necessary to strengthen cost control, stabilize coal supply prices, strengthen coal power cooperation, and promote the fine management of clean energy costs.

7.2.3.2 Actively participate in carbon market trading to reduce carbon emission reduction costs

As the electric power industry is the breakthrough of Chin's carbon emission rights trading market, in order to achieve the "dual carbo" goal, its annual available carbon quota will actually show a decreasing trend, and the part that exceeds the carbon quota needs to purchase the quota to achieve carbon emission compliance. Therefore, in the future, electric power enterprises can avoid the increase of carbon price and actively participate in carbon market trading. On the one hand, participating in carbon trading helps to convey the awareness of green responsibility to the outside world through the carbon market to enhance the corporate image; on the other hand, the active use of carbon financial instruments not only helps to reduce the cost of carbon emission reduction, but also helps to hedge the risk caused by the fluctuation of carbon trading. It is also conducive to easing the financing dilemma of enterprises so as to carry out the low-carbon transformation of energy structure more effectively.

7.2.3.3 Establish publicity and feedback mechanism within the enterprise

Since low-carbon strategy requires long-term management with diminishing marginal effect, such management needs to allocate resources reasonably according to the conditions of enterprises themselves. The strategy of an enterprise should be adaptable and adjustable. The whole strategic arrangement should be the participation of the whole enterprise to form a good feedback mechanism. Enterprises should establish a monitoring and evaluation mechanism to regularly monitor and evaluate the implementation of low-carbon development plans. These mechanisms should be able to detect problems in a timely manner and take appropriate measures to ensure that enterprises can adjust their carbon strategies in a timely manner to ensure the high utilization and high returns of resource investment. At the same time, through training and education, employees can enhance their low-carbon awareness and responsibility, so that employees can better feel and participate in the low-carbon strategy of the enterprise, and the low-carbon development strategy can be implemented and supervised for a longer time.

7.2.3.4 Focus on technological innovation to achieve green and low-carbon development

The Action Plan for Accelerating Green and Low-carbon Innovative Development of Electric Power Equipment released by the Ministry of Industry and Information Technology in 2022 also points out that China's energy production will shift from relying mainly on resources to relying more on equipment. The core of the program is to require enterprises to rely on technological innovation to enhance the green ability of electric power equipment. Power enterprises, especially thermal power enterprises, should pay more attention to the development of clean and low-carbon power generation equipment, improve energy storage technology, low-cost carbon capture and storage technology, and strengthen technical exchanges and cooperation between enterprises, promote the recycling of resources through technological innovation to meet the challenges of carbon emissions times, and achieve green and low-carbon development.

Data availability statement

The datasets presented in this article are not readily available because Company data is private. Requests to access the datasets should be directed to 498035852@qq.com.

Author contributions

JH: Writing–original draft. ZH: Data curation, Methodology, Writing–original draft. XF: Formal Analysis, Investigation, Writing–review and editing. HZ: Supervision, Validation, Writing–review and editing. MS: Conceptualization, Writing–review and editing, Writing–original draft. YZ: Validation, Writing–review and editing. CZ: Validation, Writing–review and editing.

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Conflict of interest

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Evaluation and influencing factors of green transformation in three major urban agglomerations in China

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Since the 21st century, the world has increasingly focused on the issue of sustainable development, and the green transformation issues have become a new hot topic worldwide. Green and low-carbon transformation has become an international consensus. Urban agglomerations are important connections between urban development and regional coordination, as well as important spatial carriers for economic activities. They are not only the main source of carbon emissions, but also the main battlefield for energy conservation and emission reduction. As an important field for carbon reduction, the green transformation of cities is crucial for achieving the "dual carbon" goals. This article focuses on 48 cities in the three most mature and influential urban agglomerations in China from 2011 to 2019, namely, the Beijing-Tianjin-Hebei urban agglomeration, the Yangtze River Delta urban agglomeration, and the Pearl River Delta urban agglomeration. The three-stage DEA model and Malmquist index model are used to measure the green transformation efficiency of the three urban agglomerations from both dynamic and static perspectives, and a Tobit regression model is constructed to explore the influencing factors of green transformation efficiency in urban agglomerations. Research has found that: 1) From a static perspective, the overall efficiency of green transformation in the three major urban agglomerations is at a high level, but from a temporal perspective, it shows a downward trend. The Pearl River Delta urban agglomeration is known for its green development, with the highest average efficiency of green transformation, followed by the Yangtze River Delta urban agglomeration. The Beijing-Tianjin-Hebei urban agglomeration has the lowest level of green transformation; 2) From a dynamic perspective, technological progress is the main driving factor for improving the efficiency of green transformation in the three major urban agglomerations. Therefore, the government should pay special attention to the progressiveness of technology when formulating relevant policies to promote urban green transformation; 3) From the perspective of spatiotemporal differences, there are significant differences in the spatiotemporal characteristics of green transformation among the three major urban agglomerations, and there are significant differences in green transformation strategies among different urban agglomerations. Eliminating environmental factors and random interference is necessary for accurately measuring the efficiency of green transformation in urban agglomerations; 4) From the perspective of influencing factors, factors such as industrial structure upgrading, green innovation level, and environmental regulation intensity jointly affect the efficiency of green transformation in urban agglomerations. Based on this, we should pay attention to the differences

between urban agglomerations and implement policies tailored to local conditions; Strengthen the network system of urban agglomerations and avoid conflicts between cities; Encourage green technology innovation, accelerate industrial structure upgrading, and so on. This article focuses on the issue of green transformation in urban agglomerations, and conducts research from three perspectives: efficiency measurement, influencing factors, and implementation mechanisms. A relatively systematic theoretical framework for green transformation in urban agglomerations is formed, and an evaluation index system for green transformation efficiency in urban agglomerations is constructed and optimized. The composition mechanism of the five dimensional evaluation system for transformation efficiency is analyzed, and the bottleneck and breakthrough direction of the three major urban agglomerations in China in the development process are grasped. It has a good demonstration effect on the green transformation of other urban agglomerations.

KEYWORDS

urban agglomerations, green transformation, efficiency measurement, influencing factors, low carbon development

1 Introduction

Today China's economic development has entered the New Normal, facing the challenges of speed change and structural adjustment. Economic development is hard constrained by resources and environment. The old model of "high input, high pollution" is no longer suitable for the challenges of high-quality development in the new era of China, and does not conform to China's image of a big country that is responsible for the world and ecology. In the process of globalization, previous studies revealed the distinct possibility that the 21st century will witness an urbanization—primarily in developing countries—that proceeds on a scale more massive than has ever been seen before (Masanobu Kii, 2021), suggesting that alternative urban-policy strategies may be needed for long-term sustainability. China has realized that as a major economic development country and energy consuming country, it needs to shoulder greater responsibilities. The importance and urgency of green transformation are self-evident, and exploring the path of China's green transformation is urgent.

Transformation is one of the important branches of development economics research, and the topic of transformation has been the most concerned research focus in the entire economic community for nearly half a century. Both the" Transition and Economics "written by a Belgian economist Gérard Roland (2002), and the" Theory of Transformation and Development "written by a Chinese economist Li Yining (1996) have provided a relatively complete description of the relevant issues of transformation. In the early stages, discussions on urban transformation often emerged alongside research on economic system transformation. Stark and Bruszt (1998) linked urban transformation with a large-scale process of institutional change, in fact referring to the transformation of economic system patterns. However, in recent years, there have been development constraints on resources and environment around the world, especially when the financial crisis affected the development of some resource-based cities. Not only has the development of traditional resource-based cities been difficult, but also the development of some economically sustainable cities has been frequently hindered. Therefore, the concept of green development and green transformation is gradually emerging, becoming a new breakthrough in urban economic development. Zhu Yuan (2020) pointed out that green transformation is a break from the previous model of relying solely on material scale extension to drive economic development. Instead, it constantly changes the trend of economic development while ensuring a good ecological environment. Li Zuojun (2012) believes that green transformation will become a new economic development model, shifting from resource waste and ecological environment destruction to a model of resource recycling and ecological environment friendly development. Collier et al. (2013) conducted research based on urban climate characteristics, urban facility utilization, and constraints on urban expansion, and pointed out that the use of collaborative methods can promote green and sustainable development of cities. Artmann et al. (2019) analyzed the limitations of spatial transformation on urban green development and proposed that the expansion of cities can be constrained by developing compact cities. At the same time, some foreign institutions, including Siemens (2019), have established the "Green City Index" to measure the green level of urban environmental development by dividing it into specific indicators such as carbon dioxide concentration, energy, transportation, waste, water, air, etc., and have launched tools to measure the green level of urban environmental development. Pan Haozhi et al. (2024a) examine the impacts of polycentricity as well as features of its spatial configurational on urban agglomeration efficiency, and develop an IRT-LI method to identify urban centers and sub-centers. And there are still the following areas that need to be expanded: In terms of research objects, there is a lack of comparison between multiple urban agglomerations, and there is no intersection, mixing, or integration of factors from different fields to obtain the effects, influencing factors, and specific paths of urban green transformation; In terms of research methods, common

methods such as spatial Durbin model, SBM-DEA model, and DDF-SBM cannot eliminate external environmental and statistical noise interference factors in urban green transformation (Yuan Huaxi, 2020), and there is controversy over the reliability and authenticity of evaluation results; In terms of research content, the existing evaluation index system is not yet perfect.

Urban agglomerations utilize the advantages of agglomeration factors to achieve economic growth, but have not yet changed the previous inefficient and highly polluting extensive development model. Behind economic growth is the waste of resources and the displacement of the ecological environment (Jamsson A, 2013; Guo Yanhua et al., 2020). The economic benefits are often obvious, but the problem of ecological degradation accumulates over time, which reflects the importance of addressing the contradiction between economic development and environmental protection in urban agglomerations (Verhoef and Nijkamp, 2002). The relationship between environmental damage and urban agglomeration is a complex theoretical and empirical issue, on the one hand, urban agglomeration advantages may favour environmental quality, city size is by no means a negative predictor of environmental quality (Kourtit et al., 2020). On the other hand, agglomeration provides a key mechanism for the success of manufacturing, but it also generates negative environmental externalities (Pan Haozhi et al., 2024b). With external capital investment, significant resource consumption, transportation infrastructure installation, and the migration of environmentally polluting enterprises, it is more likely to exacerbate the pressure on regional ecosystems, leading to increasingly serious problems such as environmental pollution, land scarcity, and carbon emissions, resulting in more severe ecological externalities (Huang Yin et al., 2020b; Zhong Jing et al., 2021). At present, China has planned to construct 19 urban agglomerations, among which the three major urban agglomerations of Beijing-Tianjin-Hebei urban agglomeration (BTH), Yangtze River Delta urban agglomeration (YRD), and Pearl River Delta urban agglomeration (PRD) are in a leading position in the development of urban agglomerations in China. They are the most densely populated, economically developed, and well-constructed regions in China, representing the current level and future development direction of urban agglomerations in China. Studying the efficiency and influencing factors of its green transformation can objectively and accurately grasp the bottlenecks and breakthrough directions of China's three major urban agglomerations, which has a good demonstration effect on the green transformation of other urban agglomerations (Yang Yuying et al., 2019; Fan Fei et al., 2021). This article focuses on the issue of green transformation in urban agglomerations, and conducts research from three perspectives: efficiency measurement, influencing factors, and implementation mechanisms. A relatively systematic theoretical framework for green transformation in urban agglomerations is formed, and an evaluation index system for green transformation efficiency in urban agglomerations is constructed and optimized. The composition mechanism of the five dimensional evaluation system for transformation efficiency is analyzed, and the bottleneck and breakthrough direction of the three major urban agglomerations in China in the development process are grasped. At the same time, it also provides a reference for the world to apply relevant theories to solve national practical problems, thereby improving the competitiveness and ecological environment of urban agglomerations, developing the economy and revitalizing them.

2 Material and methods

2.1 Model construction

(1) Three-Stage DEA Model

The three-stage DEA method was proposed by Fried et al. The essence of the model is to initially measure the efficiency of the research object in the first stage, and then introduce SFA regression analysis to isolate the impact of Confounding, so that the real efficiency value of green transformation can be measured in the third stage.

Stage 1: Traditional DEA-BCC model.

$$\min\left[\theta - \varepsilon\left(\mathrm{e}^{\mathrm{T}}S^{-} + e^{T}S^{+}\right)\right] \tag{2.1}$$

$$m\,\text{s.t.} = \left\{\begin{array}{c} \sum_{j=1}^{n} X_j\lambda_j + S^{-} = \theta X_0 \\ \sum_{j=1}^{n} Y_j\lambda_j - S^{+} = Y_0 \\ \sum_{j=1}^{n}\lambda_j = 1 \\ \lambda_j \geq 0, S^{-} \geq 0, S^{+} \geq 0 \end{array}\right\} \tag{2.2}$$

Where $j = 1, 2, \ldots \boldsymbol{n}$ represents the decision-making unit, $\boldsymbol{\theta}$ evaluate the efficiency of green transformation for each decision-making unit, $\boldsymbol{X}$ and $\boldsymbol{Y}$ are input and output variables, respectively. $\boldsymbol{S^{+}}$ is the relaxation variable, $\boldsymbol{S^{-}}$ is the output relaxation value, $\boldsymbol{\lambda_j}$ is the weight variable, $\boldsymbol{\varepsilon}$ represents a non Archimedes Infinitesimal. When $\theta = 1$, $S^{+} = S^{-} = 0$, indicating that the decision unit DEA is effective; When $\theta = 1$, $S^{+} \neq 0$ or $S^{-} \neq 0$ indicates that the decision unit is weakly DEA efficient, meaning that the decision unit DMU is close to the optimal resource allocation; if $\theta < 1$, indicating that the decision-making unit is not DEA effective.

Stage 2: Similar to SFA model.

$$S_{nm} = f^{m}\left(z_n, \beta_m\right) + v_{nm} + u_{nm}, \mathrm{n} = 1, 2, \ldots \mathrm{N}; \mathrm{m} = 1, 2 \ldots \mathrm{P} \tag{2.3}$$

Among them, $\boldsymbol{S_{nm}}$ is the input relaxation variable, $\boldsymbol{f^{m}(z_n, \beta^{m})}$ is the corresponding random frontier function, and $\boldsymbol{z_n}$=($\boldsymbol{z_{1n}}$,$\boldsymbol{z_{2n}}$, … $\boldsymbol{z_{kn}}$)represents external environmental factors, $\boldsymbol{\beta^{m}}$ is the corresponding coefficient; $\boldsymbol{v_{nm} + u_{nm}}$ is a mixed residual term, $\boldsymbol{v_{nm}}$ representing random error and $\boldsymbol{v_{nm} \sim N(0, \delta_{mv}^{2})}$, $\boldsymbol{u_{nm}}$ representing management inefficiency and $\boldsymbol{u_{nm} \sim N^{+}(\mu_m, \delta_{mu}^{2})}$, $\boldsymbol{u_{nm}}$ and $\boldsymbol{v_{nm}}$ are independent of each other.

Since Fried did not explicitly give a formula for separating management inefficiency terms in his research, this paper uses the management inefficiency formula proposed by Jondrow (2012) to calculate the Estimator of $\boldsymbol{u_{nm}}$ and $\boldsymbol{v_{nm}}$. The separation formula is obtained as follows: $\boldsymbol{\gamma = \sigma^{2}{}_{u}+\sigma^{2}{}_{v}/\sigma^{2}{}_{u}}$, the closer the $\boldsymbol{\gamma}$ is to 0, the greater the impact of random error; The

closer the γ is to 1, the greater the impact of management inefficiency.

Stage 3: Adjusted DEA model. By applying the DEA-BCC model again to calculate the efficiency of the input variables and original output variables adjusted by SFA regression, the actual value of the green transformation efficiency of urban agglomerations, excluding external environmental factors and random errors, can be obtained. At this time, the actual efficiency value calculated is more rigorous and accurate compared to the results of the first stage.

(2) Malmquist Index Model

Due to the limitations of the three-stage DEA model, it is not possible to measure the dynamic trend of cross cycle efficiency values of decision-making units. Based on this, the Malmquist index model is introduced to evaluate the dynamic efficiency of green transformation in urban agglomerations.

According to the Malmquist index decomposition method proposed by Fare et al. (1994), if there are r decision units, t+1 periods, X_r^t represents the input level of decision unit r in period t, Y_r^t represents the output level of decision unit r in period $(t = 1, 2, \ldots, T-1, r = 1, 2, \ldots, n)$, and $D_r^t\ (X_r^{t+1}, Y_r^{t+1})$ represents the DEA efficiency of decision unit r in period t+1 calculated based on time t, the Malmquist index model from period t to period t+1 is defined and decomposed as follows:

$$M_r = \left[\frac{D_r^t(X_r^{t+1}, Y_r^{t+1})}{D_r^t(X_r^t, Y_r^t)} * \frac{D_r^{t+1}(X_r^{t+1}, Y_r^{t+1})}{D_r^{t+1}(X_r^t, Y_r^t)}\right]^{\frac{1}{2}} \tag{2.4}$$

$$= \frac{D_r^{t+1}(X_r^{t+1}, Y_r^{t+1})}{D_r^t(X_r^t, Y_r^t)} * \left[\frac{D_r^t(X_r^{t+1}, Y_r^{t+1})}{D_r^{t+1}(X_r^{t+1}, Y_r^{t+1})} * \frac{D_r^t(X_r^t, Y_r^t)}{D_r^{t+1}(X_r^t, Y_r^t)}\right]^{\frac{1}{2}} \tag{2.5}$$

$$= \frac{D_v^{t+1}(X_v^{t+1}, Y_v^{t+1})}{D_v^t(X_v^t, Y_v^t)} * \left[\frac{D_r^{t+1}(X_r^{t+1}, Y_r^{t+1})}{D_v^{t+1}(X_v^{t+1}, Y_v^{t+1})} * \frac{D_v^t(X_v^t, Y_v^t)}{D_r^t(X_r^t, Y_r^t)}\right] \tag{2.6}$$

(3) Tobit Model

The Tobit model, also known as the truncated regression model or censored regression model, can be used as a type of limited dependent variable regression due to some observations having values of 0, although the values of the dependent variable are generally continuous numerically. Restricted dependent variable regression can be used to determine whether a specific dependent variable is related to another specific observation, and can determine whether the dependent variable will be affected by other factors based on these observations. This model was first proposed by James Tobin, the Nobel laureate in economics. At first, it was only used to analyze the expenditure of household durable goods. Later, it was gradually expanded to a variety of situations and was widely used.

The basic form of the Tobit model is as follows:

$$\begin{aligned} &Y_i^* = X_i^T\beta + \mu_i \\ &\mu_i \sim N(0, \sigma^2) \\ &Y_i = \begin{cases} Y_i^*, Y_i^* > 0 \\ 0, Y_i^* \le 0 \end{cases} \end{aligned} \tag{2.7}$$

In this equation, Y_i is the restricted dependent variable of the i group of samples, and X_i is the explanatory variable, β is a vectorized expression of variable parameters, where the random disturbance term μ_i follows a normal distribution, $i = 1, 2, \ldots n$.

The model can also be simplified as follows:

$$y = \max(0, X_i^T\beta + \mu_i) \tag{2.8}$$

2.2 Variables and data

(1) Sample Selection

By 2019, the planning and layout of 19 urban agglomerations in China have been completed, and a new regional development model with urban agglomerations as the core for growth has been gradually implemented. Among them, the BTH, YRD, and PRD, relying on their unique geographical advantages and political preferences, have developed ahead of other urban agglomerations and become the most international and representative urban agglomerations in China. The BTH, YRD, and PRD are pioneers in China's development. They have a clearer definition of concepts and policy planning, and have relatively close cooperation in various aspects such as actual economy and technology. Compared to other urban agglomerations that are in the planning or concept proposal stage, selecting these three major urban agglomerations as research objects is representative. Therefore, based on the national planning and the actual development of the eastern coastal urban agglomeration, this paper selects 48 cities in the BTH, YRD, and the PRD as the research objects, as shown[1] in Figure 1.

(2) Indicators and Data Sources

Based on the existing research results and the dynamic behavior perspective of the implementation of green transformation in the three urban agglomerations, this paper determines the input variables of green transformation in the three urban agglomerations from the three dimensions of human investment, capital investment and land investment. These dimensions are represented by three indicators: total green investment, total green talents and green area.

Based on the basic connotation of the concept of green transformation, and ultimately realize the harmonious development of human, nature, economy and society, the output variables of this study are determined from five dimensions, including economic growth, industrial transformation, resource conservation, environmental friendliness and people's livelihood improvement. In this study, seven indicators are used, namely, GDP growth rate, the proportion of added value of the tertiary industry, energy consumption per unit of GDP, *per capita* disposable

1 The BTH urban agglomeration includes 13 cities: Beijing, Tianjin, Shijiazhuang, Tangshan, Qinhuangdao, Handan, Xingtai, Baoding, Zhangjiakou, Chengde, Cangzhou, Langfang, Hengshui; The YRD urban agglomeration includes 26 cities: Shanghai, Nanjing, Wuxi, Changzhou, Suzhou, Nantong, Yancheng, Yangzhou, Zhenjiang, Taizhou, Hangzhou, Ningbo, Huzhou, Jiaxing, Shaoxing, Jinhua, Zhoushan, Taizhou, Hefei, Wuhu, Ma'anshan, Tongling, Anqing, Chuzhou, Chizhou, Xuancheng; The PRD urban agglomeration includes 9 cities: Guangzhou, Shenzhen, Zhuhai, Foshan, Jiangmen, Zhaoqing, Huizhou, Dongguan, Zhongshan

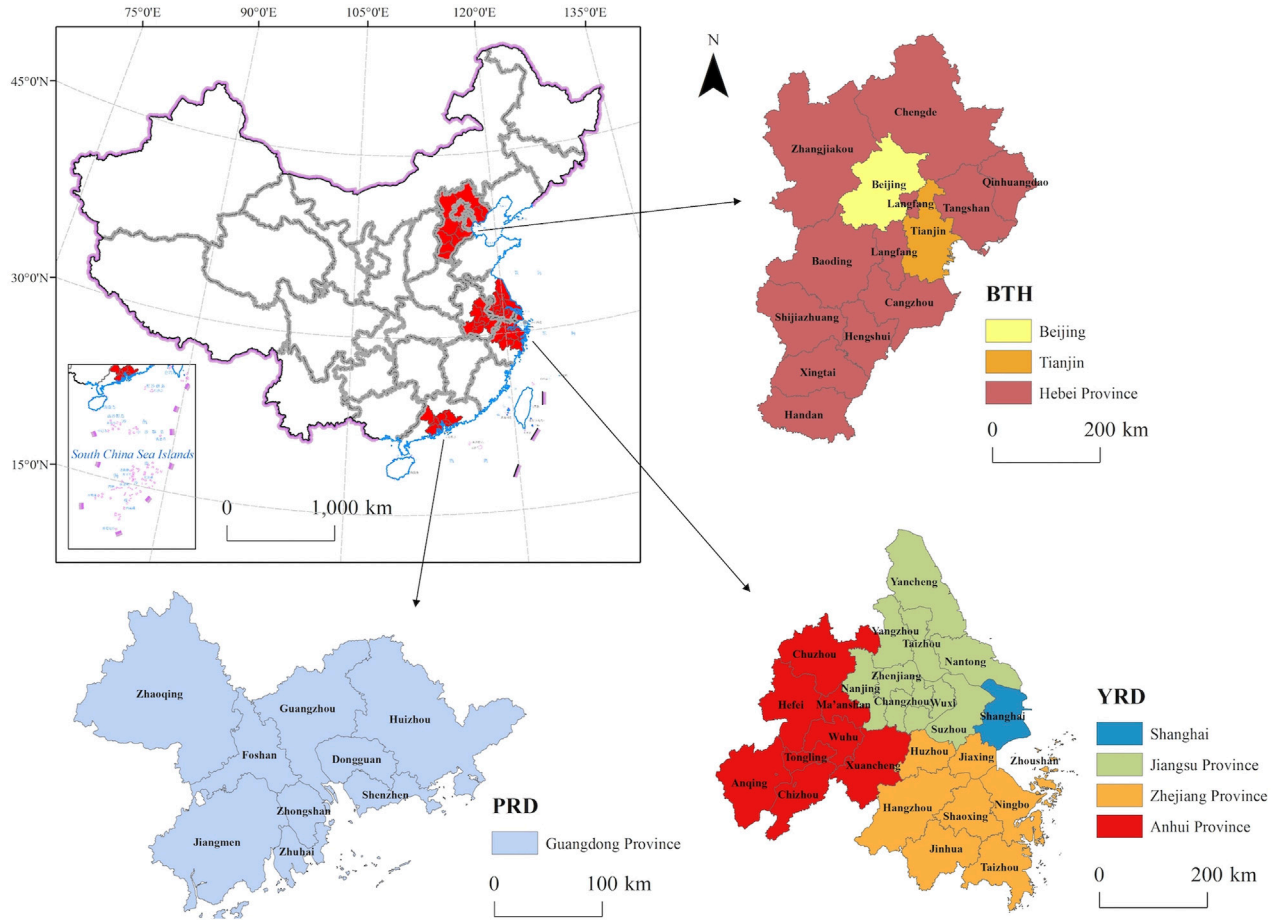


FIGURE 1
Geographical distribution map of the three major urban agglomerations in China.

income of urban residents, *per capita* green space area of urban parks, sulfur dioxide emissions and comprehensive utilization rate of industrial solid waste, which represent the above dimensions.

As for environmental variables, considering the impact of external factors such as economic and social factors, economic structure, energy consumption structure and technological innovation level are selected as the external environmental variables affecting the green transformation of urban agglomerations. These external variables are measured by three indicators: the proportion of added value of the secondary industry, the proportion of coal consumption in comprehensive energy consumption, and the number of patents approved *per capita*.

Therefore, the green transformation efficiency evaluation system of the three urban agglomerations preliminarily constructed in this paper is shown in Table 1. The selection of indicators follows the principles of comprehensiveness, balance, rationality and availability.

Considering the completeness and availability of data, as well as the significant impact of the pandemic fluctuations on research data from 2020, this article selects statistical data from the three major urban agglomerations in China from 2011 to 2019. The relevant data in the study comes from the statistical systems of various levels of government in China, including the China Urban Statistical Yearbook, Provincial Statistical Yearbook, Urban Statistical Yearbook, and National Economic and Social Development Statistical Bulletin. Some missing data is supplemented using interpolation method. Some index data are indirect data, which are calculated from the original data (Table 2).

In scholars' research on the influencing factors of urban green transformation, it is generally believed that factors such as industrial structure, technological progress, and institutional environment are closely related to urban green transformation. The industrial structure upgrade can further promote regional coordinated green development and high-quality development (Li Zihao and Mao jun, 2018; Peng Jizeng et al., 2020). Green innovation level is conducive to promoting the development of green economy in cities (LOREK S, 2014; Feng et al., 2019). Environmental regulatory measures will significantly increase the operating costs of enterprises, resulting in a "crowding out effect" and ultimately inhibiting urban green transformation (Yin et al., 2015). A sound infrastructure construction is the prerequisite and foundation for promoting urban green transformation (Wang et al., 2022). Most developed countries will transfer local high energy consuming and high emission enterprises to developing countries to suppress regional green development (Wu Chuanqing and Song Xiaoxiao, 2018). Referring to these studies and based on the principle of

TABLE 1 Index system for measuring green transformation efficiency of three major urban agglomerations in China.

	Variable	Evaluation indicator	Indicator interpretation	Data sources
Input variable	Capital investment	Total amount of green investment	Including total investment in environmental protection, technological innovation, and education; reflecting the status of green capital investment in green transformation	China urban statistical yearbook; provincial statistical yearbook
	Human resource investment	Total number of green talents	Including the total number of talents in environmental protection, technological innovation, and education; reflecting the green human resource investment in green transformation	Provincial statistical yearbook; statistical yearbook of each city
	Land investment	Total quantity of green areas	Reflecting the green space investment in green transformation	China urban statistical yearbook
Output variable	Economic growth	GDP growth rate	Reflect the effectiveness of green transformation in promoting economic development	China urban statistical yearbook
	Industrial transformation	Proportion of added value in the tertiary industry	Reflect the effectiveness of green transformation in promoting industrial and economic structural upgrading	China urban statistical yearbook
	Resource saving	Energy consumption per unit of GDP	Reflect the effectiveness of green transformation in promoting energy and other resource conservation	Statistical yearbook of each city; Municipal Statistical Bulletin
	Environmental governance	The treatment of waste water and synthesis utilization rate of industrial waste	Reflect the role of green transformation in promoting industrial pollution control	China urban statistical yearbook
	Improvement of livelihood	Green coverage area of built-up area *per capita*	Reflect the role of green transformation in improving urban living environment	China urban statistical yearbook
		Disposable income of urban residents *per capita*	Reflect the role of green transformation in improving residents' wealth and welfare	Provincial Statistical Yearbook; Municipal Statistical Bulletin
Environment variable	Economic structure	Proportion of added value in the secondary industry	Reflecting the impact of economic structure on green transformation	China urban statistical yearbook
	Energy consumption structure	Proportion of coal consumption	Reflecting the impact of energy consumption structure on green transformation	Statistical yearbook of each city; Municipal Statistical Bulletin
	Technological innovation level	The number of approved patents *per capita*	Reflecting the impact of technological innovation level on green transformation	China urban statistical yearbook

TABLE 2 Indicator calculation formula.

Index	Calculation formula
Total amount of green investment	Investment in environmental protection + investment in science and innovation + investment in education
Total number of green talents	Number of environmental protection talents + number of scientific and creative talents + number of educational talents
Energy consumption per unit of GDP	Comprehensive energy consumption/GDP
Green coverage area of built-up area *per capita*	Green coverage area of built-up area/household registration population at the end of the year
Proportion of coal consumption	Coal consumption/comprehensive energy consumption

accessibility of statistical data, this article selects 5 influencing factors from two aspects: government dominant factors and objective environmental factors for analysis. From the perspective of government management, the upgrading of industrial structure, the level of green innovation, and the intensity of environmental regulations are selected as the government leading factors affecting the green transformation of urban agglomerations. From the perspective of external environment, infrastructure construction and the degree of openness are selected as objective environmental factors affecting the green transformation of urban agglomerations.

The key variables selected in this article are as follows (Table 3):

① Explanatory variable: urban green transformation. Measure the static efficiency value of green transformation in urban agglomerations.

TABLE 3 Explanation of influencing factors and variables.

Meaning of variables	Measurement of variables	Units of variables
Explained variable	Static efficiency values of urban green transformation	—
Explanatory variable	—	—
Industrial Structure Upgrade (ISU)	The proportion of the tertiary industry to GDP	%
Green Innovation Level (GIL)	Number of R&D personnel	10,000 people
Environmental Regulation Intensity (ERI)	The discharge quantity of industrial wastewater	10,000 tons
Infrastructure Construction (IC)	Per capita postal and telecommunications business volume	one yuan per person
Extent of openness to the outside world (FDI)	Foreign direct investment	ten thousanddollars

② Explanatory variable: a. Industrial structure upgrade (ISU). Measured by the proportion of the tertiary industry in the city's GDP. b. Green innovation level (GIL). Measured by the number of R&D personnel in the city. c. Environmental regulation intensity (ERI). Measured by the amount of industrial wastewater discharge in the city. d. Infrastructure construction (IC). Measured by the *per capita* postal and telecommunications business volume in the city. e. The extent of openness to the outside world (FDI). Measured by the total amount of foreign direct investmentin cities.

3 Empirical results

3.1 Static efficiency evaluation results

(1) Comprehensive efficiency evaluation results in the first stage

Firstly, the input-oriented BCC model was used to calculate the comprehensive efficiency of green transformation in 48 cities of China's three major urban agglomerations (Table 4).

According to Table 4, among the three major urban agglomerations from 2011 to 2019, the green transformation efficiency of 48 cities in China's three major urban agglomerations was almost all above 0.6, indicating that the overall green transformation level of the three major urban agglomerations is relatively high; Among them, the average comprehensive efficiency of green transformation in seven cities, Cangzhou, Zhoushan, Ma'anshan, Tongling, Chizhou, Foshan, and Zhongshan, reached 1, which is the highest among all comprehensive efficiency results, indicating that their green transformation level is superior to other cities. Among these seven cities with a comprehensive efficiency of 1, four are located in the YRD; Although the average efficiency values of green transformation in most cities are between 0.6 and 1, the efficiency values of Qinhuangdao City are 0.437, Baoding City is 0.572, Chengde City is 0.593, and Changzhou City is 0.479. They are the four cities with efficiency values below 0.6 among all cities. Qinhuangdao City, Baoding City, and Chengde City are located in the BTH, while Changzhou City is located in the YRD; In addition, although the overall green transformation comprehensive efficiency values of 48 cities in China's three major urban agglomerations were relatively high from 2011 to 2019, the time trend is not optimistic. The average green transformation efficiency values of the YRD and PRD show a downward trend, while the efficiency values of the BTH have not changed much, but are at a lower level compared to the other two urban agglomerations. Overall, the PRD is known for its green development, with the highest average efficiency value of green transformation. This result has also been reflected in the research of other scholars or institutions, such as the "National New Urbanization Report 2016"; Secondly, the YRD has a similar level of green transformation to the PRD, as it covers multiple provinces and has always been a prosperous place with the highest economic output. At the same time, it is also a livable place with a good ecological environment; The BTH is centered around the two major super cities of Beijing and Tianjin, promoting the coordinated development of the urban agglomeration. However, the two cities' dominant development has not achieved good agglomeration and central radiation effects. The above results indicate that the overall level of green transformation comprehensive efficiency in 48 cities of China's three major urban agglomerations is relatively high, but it shows a slight downward trend in terms of time trend. Therefore, it is necessary to take more action plans to continuously improve the green transformation efficiency of cities.

Specifically, the comprehensive efficiency values of green transformation in the three major urban agglomerations from 2011 to 2019 were plotted as a line chart, as shown in Figure 2.

There are significant differences in the comprehensive efficiency of green transformation among the three major urban agglomerations in China. Overall, the comprehensive efficiency of green transformation in the YRD and PRD is significantly higher than that in the BTH, both ranging from 0.75 to 0.9, indicating that the actual effect of green transformation in the YRD and PRD is good. However, the overall efficiency fluctuation of green transformation in the BTH is not significant, stable at around 0.73. Before 2014, the green transformation efficiency of the PRD was very high, but it began to sharply decline after reaching its peak in 2014 and reached its lowest level in 2018; The green transformation efficiency of the YRD slowly increased from 2011 to 2015, and also began to decline slightly after reaching its peak in 2015; The fluctuation trend of the BTH is not obvious. However, overall, the green transformation efficiency of the three major urban agglomerations showed a trend of first increasing and then decreasing between 2011 and 2018. However, after reaching the lowest level in 2018, the green transformation efficiency values of the three major urban agglomerations showed a significant rebound in 2019.

TABLE 4 Comprehensive efficiency of green transformation in China's three major urban agglomerations from 2011 to 2019.

Region	City	2011	2012	2013	2014	2015	2016	2017	2018	2019	Average
BTH	Beijing	0.845	0.868	0.986	0.89	0.907	0.968	1	1	1	0.940
	Tianjin	1	1	1	1	0.924	0.953	0.884	0.843	0.872	0.942
	Shijiazhuang	0.674	0.702	0.708	0.704	0.738	0.653	0.664	0.535	0.542	0.658
	Tangshan	0.721	0.751	0.779	0.839	0.79	0.751	0.623	0.614	0.469	0.704
	Qinhuangdao	0.432	0.43	0.439	0.458	0.429	0.436	0.432	0.407	0.469	0.437
	Handan	0.629	0.589	0.663	0.595	0.643	0.616	0.639	0.635	0.642	0.628
	Xingtai	0.589	0.609	0.668	0.623	0.729	0.794	0.692	0.728	0.729	0.685
	Baoding	0.654	0.674	0.698	0.632	0.519	0.523	0.512	0.451	0.489	0.572
	Zhangjiakou	0.696	0.632	0.681	0.604	0.786	0.694	0.964	1	1	0.784
	Chengde	0.592	0.576	0.584	0.659	0.615	0.574	0.549	0.524	0.665	0.593
	Cangzhou	1	1	1	1	1	1	1	1	1	1
	Langfang	0.673	0.674	0.761	0.794	0.763	0.733	0.712	0.745	0.748	0.734
	Hengshui	0.854	0.85	0.902	0.835	0.898	1	0.729	0.815	0.904	0.865
YRD	Shanghai	1	1	1	0.984	1	1	1	1	1	0.998
	Nanjing	0.768	0.807	0.86	0.847	0.815	0.765	0.763	0.698	0.654	0.775
	Wuxi	0.841	0.957	0.907	1	1	0.978	0.997	0.946	0.937	0.951
	Changzhou	0.472	0.475	0.463	0.547	0.467	0.482	0.449	0.456	0.5	0.479
	Suzhou	1	0.894	0.883	0.942	0.904	0.907	0.954	0.924	0.923	0.926
	Nantong	0.828	0.748	0.803	0.837	0.838	0.84	0.918	0.89	0.971	0.853
	Yancheng	0.705	0.703	0.783	0.79	0.764	0.76	0.77	0.778	0.777	0.759
	Yangzhou	0.754	0.881	0.939	0.893	0.936	0.889	0.91	0.9	0.985	0.899
	Zhenjiang	0.927	0.932	0.975	0.957	0.938	0.935	0.935	0.831	0.855	0.921
	Taizhou	0.636	0.728	0.695	0.691	0.654	0.64	0.63	0.56	0.542	0.642
	Hangzhou	1	0.959	0.938	0.991	1	0.978	1	1	1	0.985
	Ningbo	1	0.99	0.981	1	0.946	0.887	0.87	0.747	0.741	0.907
	Jiaxing	0.858	0.802	0.875	0.899	0.876	0.827	0.861	0.774	0.805	0.842
	Huzhou	0.832	0.92	0.898	0.895	0.886	0.839	0.81	0.782	0.817	0.853
	Shaoxing	0.988	0.916	0.886	0.892	0.83	0.804	0.849	0.759	0.749	0.853
	Jinhua	1	0.976	1	1	1	0.915	0.902	0.86	0.926	0.953
	Zhoushan	1	1	1	1	1	1	1	1	1	1
	Taizhou	0.719	0.708	0.778	0.777	0.764	0.749	0.705	0.74	0.715	0.739
	Hefei	0.639	0.622	0.642	0.648	0.698	0.53	0.617	0.55	0.595	0.616
	Wuhu	0.614	0.638	0.607	0.65	0.65	0.645	0.637	0.666	0.689	0.644
	Ma'anshan	1	1	1	1	1	1	1	1	1	1
	Tongling	1	1	1	1	1	1	1	1	1	1
	Anqing	0.63	0.631	0.63	0.636	1	0.937	0.599	0.615	0.642	0.702
	Chuzhou	0.671	0.646	0.684	0.647	0.668	0.603	0.617	0.607	0.793	0.660
	Chizhou	1	1	1	1	1	1	1	1	1	1

(Continued on following page)

TABLE 4 (*Continued*) Comprehensive efficiency of green transformation in China's three major urban agglomerations from 2011 to 2019.

Region	City	2011	2012	2013	2014	2015	2016	2017	2018	2019	Average
	Xuancheng	0.588	0.727	0.788	0.697	0.735	0.698	0.681	0.685	0.676	0.697
PRD	Guangzhou	0.928	0.872	0.877	1	0.919	0.834	0.694	0.68	0.555	0.818
	Shenzhen	1	1	0.824	1	0.984	1	1	1	1	0.979
	Zhuhai	0.965	0.821	1	0.913	0.899	1	0.74	0.803	0.902	0.894
	Foshan	1	1	1	1	1	1	1	1	1	1
	Jiangmen	0.744	0.836	0.781	0.735	0.674	0.689	0.681	0.626	0.755	0.725
	Zhaoqing	0.619	0.743	0.735	0.746	0.698	0.764	0.74	0.704	0.631	0.709
	Huizhou	0.705	0.711	0.684	0.662	0.64	0.623	0.645	0.682	0.656	0.668
	Dongguan	0.67	0.765	0.648	0.726	0.679	0.485	0.485	0.489	0.5	0.605
	Zhongshan	1	1	1	1	1	1	1	1	1	1

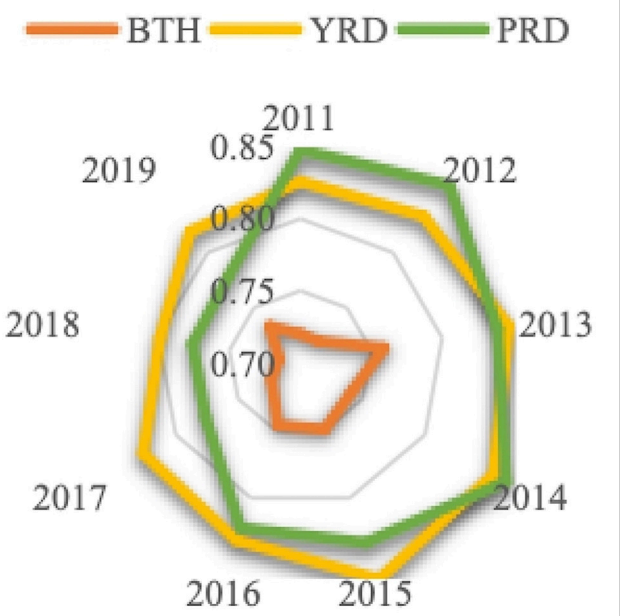


FIGURE 2
Trends in the comprehensive efficiency of green transformation in China's three major urban agglomerations from 2011 to 2019.

(2) Impacts of external environmental factors on the green transformation efficiency in the second stage

In order to eliminate the effects of random disturbances and inefficient management, and make the measured efficiency of green transformation in urban agglomerations more reasonable and reliable, the SFA method was conducted, and the results are shown in Table 5.

The results indicate that the three relaxation variables include the total amount of green investment, the total number of green talents, and the relaxation values of green area are all greater than 0.5. Based on the influence of three environmental factors, the unilateral error LR test results are all greater than the significant values of the mixed chi square distribution test. All four models are valid, indicating that the SFA method is effective in separating environmental impacts, statistical noise, and managing inefficiency. Specifically:

1) The proportion of added value in the second industry: The coefficients of the proportion of added value in the second industry in Model 1 and Model 3 are both negative and significant at the 1% significance level, while the coefficients in Model 2 are positive and significant at the 5% significance level. This indicates that an increase in the proportion of added value in the secondary industry will lead to a decrease in the total green investment and green area, while also leading to an increase in the total number of green talents.
2) Coal consumption proportion: All coefficients of coal consumption proportion are positive and significant at the significance level of 5%. This indicates that an increase in the proportion of coal consumption will lead to an increase in total green investment, total green talent, and green area.
3) Number of patents granted *per capita*: All coefficients for the number of patents granted *per capita* are negative and significant at the 1% significance level. This indicates that with the increase in the number of patents granted *per capita*, the innovation level of cities can be improved, promoting technological progress and industrial upgrading, thereby reducing the investment of cities in green talents, green capital, and green land.

(3) Real efficiency evaluation results in the third stage

In the third stage, the actual efficiency values of green transformation in 48 cities of China's three major urban agglomerations were obtained by separating the effects of inefficient management and random interference in the second stage, adjusting investment indicators, and conducting further calculations.

According to Table 6, compared to comprehensive efficiency, the actual efficiency of green transformation in 48 cities of China's three major urban agglomerations shows a significant upward trend. The actual efficiency is almost all above 0.7, indicating that after excluding the impact of environmental factors, the overall green transformation level of the three major urban agglomerations is

TABLE 5 SFA estimation results.

Variable	Model 1		Model 2		Model 3	
Explained variable	Total green investment		Total number of green talents		Green area	
	coefficient	t-statistics	coefficient	t-statistics	coefficient	t-statistics
Constant	−68857.501***	−21.796	−1.384***	−3.472	−383.773***	−3.161
Proportion of the added value of the secondary industry	−227335.8***	−539.347	5.634**	2.496	−3116.304***	−12.113
Proportion of the coal consumption	117,811.45***	51.643	0.359**	2.486	1171.204***	2.934
Number of patents granted *per capita*	−1272.463***	4.587	−1.414***	−6.429	−14.455***	2.948
σ^2	17,368,141,000	17,365,927,000	14.371	4.256	2347137.9	730,497.04
γ	0.81	47.787	0.81	17.259	0.53	7.987
LR	213.88***		348.65***		534.71***	

Note: ***, ** and * indicates the 1%, 5% and 10% significance level respectively.

relatively high; Among them, Cangzhou, Shanghai, Hangzhou, Jinhua, Zhoushan, Ma'anshan, Tongling, Chizhou, Foshan, and Zhongshan have an average actual efficiency of 1 in green transformation. Among these ten cities with a comprehensive efficiency of 1, seven cities are located in the YRD.

Specifically, the actual efficiency values of green transformation in the three major urban agglomerations from 2011 to 2019 were plotted as a line chart, as shown in Figure 3.

There are significant differences in the actual efficiency of green transformation among the three major urban agglomerations in China. Overall, the actual efficiency of green transformation in the YRD and PRD is significantly higher than that in the BTH, with efficiency values above 0.85, indicating that the actual effect of green transformation in the YRD and PRD is good. Before 2014, the green transformation efficiency of the PRD was very high, but it began to sharply decline after reaching its peak in 2014 and reached its lowest level in 2018; The green transformation efficiency of the YRD slowly increased from 2011 to 2014, and also began to decline slightly after reaching its peak in 2014; The efficiency value of the BTH has been showing a serious downward trend from 2013 to 2018, reaching the lowest value of 0.782 in 2018. However, overall, after reaching the lowest level in 2018, the green transformation efficiency values of the three major urban agglomerations showed a slight rebound in 2019.

3.2 Dynamic efficiency evaluation results

The Malmquist index model was used to measure the green transformation efficiency of the three major urban agglomerations in China from 2011 to 2019. The comprehensive efficiency values and efficiency decomposition values of green transformation in 48 cities of the three major urban agglomerations in China at different periods were calculated, and the results are shown in Table 7.

Firstly, the average green transformation efficiency of China's three major urban agglomerations from 2011 to 2019 was 0.982, which decreased by 1.8% on average over the past 9 years, presenting a negative growth trend. The technical efficiency value is 0.997, an overall decrease of 0.3% compared to before. The average change in technological progress is 0.984, a decrease of 1.6% overall compared to before. The average scale efficiency is 0.992, a decrease of 0.8% overall compared to before. The average pure technical efficiency is 1.005, an overall increase of 0.5% compared to before. Therefore, the change in the average value of comprehensive technical efficiency is mainly influenced by scale efficiency, and the positive impact of pure technical efficiency on comprehensive technical efficiency is offset by the decrease in scale efficiency. At the same time, the impact of changes in the technological progress index on urban transformation efficiency is much greater than the impact of technological efficiency on urban transformation efficiency. Therefore, it can be concluded that the lag of technological progress is the main reason for the decline in the comprehensive efficiency of green transformation in urban agglomerations in China.

Plot the comprehensive efficiency values and efficiency decomposition values of green transformation in 48 cities of China's three major urban agglomerations in different periods into a line chart to grasp their changing trends. The results are shown in Figure 4.

It can be seen that in the nine periods from 2011 to 2019, the efficiency of green transformation in urban agglomerations showed an upward trend from 2012 to 2014 and from 2015 to 2016, while in other periods it remained in a downward trend. Based on the specific decomposition situation, when the technological progress index decreases or rises, total factor productivity will also experience the same decrease or increase. The trend of change in total factor productivity is almost identical to that of technological progress, but does not overlap. The reason is that the impact of changes in technological efficiency on urban transformation efficiency offsets some of the impact of changes in technological progress, The trend of the efficiency of green transformation in urban agglomerations almost entirely depends on the change index of technological progress.

From Figure 5, it can be seen that the total factor productivity of the three major urban agglomerations in China was less than 1 from 2011 to 2019, indicating that the overall efficiency of green transformation in the three urban agglomerations decreased during this period. Among them, the average tfpch of the BTH is 0.983, the average tfpch of the YRD is 0.982, and the average tfpch of the PRD is 0.983, with similar decreases. Based on the Malmquist

TABLE 6 Real efficiency of green transformation in China's three major urban agglomerations from 2011 to 2019.

Region	City	2011	2012	2013	2014	2015	2016	2017	2018	2019	Average
BTH	Beijing	1	1	1	0.971	0.918	0.829	0.817	0.837	0.789	0.907
	Tianjin	1	1	1	1	0.974	0.974	0.939	0.899	0.905	0.966
	Shijiazhuang	0.832	0.776	0.825	0.788	0.823	0.74	0.708	0.622	0.637	0.750
	Tangshan	0.806	0.878	0.899	0.939	0.896	0.864	0.737	0.707	0.55	0.808
	Qinhuangdao	0.562	0.54	0.538	0.542	0.521	0.529	0.514	0.493	0.567	0.534
	Handan	0.833	0.717	0.812	0.74	0.761	0.731	0.75	0.711	0.697	0.750
	Xingtai	0.829	0.836	0.881	0.852	0.936	0.913	0.841	0.83	0.827	0.861
	Baoding	0.845	0.886	0.902	0.854	0.67	0.724	0.745	0.657	0.742	0.781
	Zhangjiakou	0.944	0.868	0.797	0.853	0.894	0.838	0.851	0.919	0.921	0.876
	Chengde	0.86	0.835	0.85	0.928	0.859	0.856	0.836	0.788	0.884	0.855
	Cangzhou	1	1	1	1	1	1	1	1	1	1
	Langfang	0.901	0.878	0.94	0.919	0.913	0.905	0.88	0.92	0.96	0.913
	Hengshui	1	1	1	0.974	0.955	0.918	0.83	0.789	0.872	0.926
YRD	Shanghai	1	1	1	1	1	1	1	1	1	1
	Nanjing	0.892	0.873	0.933	0.88	0.844	0.819	0.803	0.761	0.705	0.834
	Wuxi	0.923	1	0.997	1	1	1	1	1	1	0.991
	Changzhou	0.701	0.686	0.65	0.744	0.622	0.667	0.61	0.619	0.638	0.660
	Suzhou	0.701	0.686	0.65	0.744	0.622	0.667	0.61	0.619	0.638	0.660
	Nantong	0.968	0.895	0.915	0.933	0.942	0.975	0.98	0.994	1	0.956
	Yancheng	0.977	0.909	0.936	0.896	0.875	0.9	0.923	0.92	0.912	0.916
	Yangzhou	0.949	0.976	0.992	0.97	0.975	0.97	0.958	0.948	1	0.971
	Zhenjiang	0.995	0.985	1	1	0.98	0.991	0.977	0.922	0.931	0.976
	Taizhou	0.786	0.774	0.743	0.762	0.684	0.69	0.661	0.62	0.607	0.703
	Hangzhou	1	1	1	1	1	1	1	1	1	1
	Ningbo	1	1	1	1	1	0.946	0.965	0.824	0.807	0.949
	Jiaxing	0.981	0.962	0.967	0.962	0.949	0.939	0.985	0.935	0.926	0.956
	Huzhou	0.968	0.989	0.975	0.984	0.956	0.963	0.908	0.899	0.908	0.950
	Shaoxing	1	1	0.958	0.979	0.936	0.923	0.921	0.858	0.873	0.939
	Jinhua	1	1	1	1	1	1	1	1	1	1
	Zhoushan	1	1	1	1	1	1	1	1	1	1
	Taizhou	0.922	0.875	0.922	0.909	0.891	0.909	0.881	0.902	0.89	0.900
	Hefei	0.759	0.766	0.82	0.798	0.813	0.67	0.717	0.687	0.678	0.745
	Wuhu	0.88	0.825	0.854	0.876	0.863	0.871	0.864	0.879	0.889	0.867
	Ma'anshan	1	1	1	1	1	1	1	1	1	1
	Tongling	1	1	1	1	1	1	1	1	1	1
	Anqing	0.903	0.904	0.849	0.843	0.873	0.844	0.884	0.907	0.891	0.878
	Chuzhou	0.98	0.933	0.912	0.922	0.927	0.884	0.895	0.901	1	0.928
	Chizhou	1	1	1	1	1	1	1	1	1	1

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TABLE 6 (*Continued*) Real efficiency of green transformation in China's three major urban agglomerations from 2011 to 2019.

Region	City	2011	2012	2013	2014	2015	2016	2017	2018	2019	Average
	Xuancheng	1	1	1	1	0.983	0.973	0.978	0.944	0.938	0.980
PRD	Guangzhou	0.986	0.943	0.975	1	0.966	0.914	0.757	0.761	0.61	0.879
	Shenzhen	1	1	0.861	1	1	1	1	1	1	0.985
	Zhuhai	1	1	1	1	1	1	0.857	0.882	0.971	0.968
	Foshan	1	1	1	1	1	1	1	1	1	1
	Jiangmen	0.937	0.949	0.911	0.876	0.754	0.806	0.796	0.761	0.855	0.849
	Zhaoqing	0.894	0.968	0.956	1	0.907	0.866	0.867	0.813	0.747	0.891
	Huizhou	0.9	0.852	0.808	0.841	0.739	0.808	0.794	0.805	0.783	0.814
	Dongguan	0.766	0.864	0.802	0.819	0.754	0.666	0.642	0.649	0.627	0.732
	Zhongshan	1	1	1	1	1	1	1	1	1	1

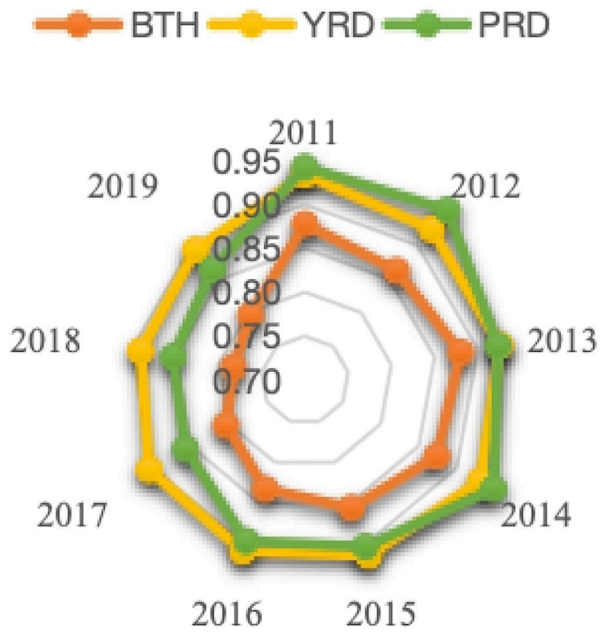


FIGURE 3
Trends in the real efficiency of green transformation in China's three major urban agglomerations from 2011 to 2019.

index decomposition, from 2011 to 2019, the average change in technological efficiency of the BTH was 0.989, with the largest decrease. The average change in technological efficiency of the YRD and PRD was 0.997 and 0.993, respectively. The techch of the BTH is 0.995, while the techch of the YRD and the PRD are 0.986 and 0.99, respectively. The decline in the YRD is relatively large. From this, it can be seen that the changes in the technological progress index have a much greater impact on the efficiency of urban transformation than the impact of technological efficiency on urban transformation efficiency. The lagging technological progress hinders the improvement of green transformation efficiency in the three major urban agglomerations.

TABLE 7 Dynamic efficiency and decomposition of green transformation in three major urban agglomerations in China from 2011 to 2019.

Year	effch	Techch	pech	sech	tfpch
2011–2012	1.011	0.913	1.023	0.988	0.923
2012–2013	1.019	0.986	1.017	1.002	1.005
2013–2014	1.005	1.009	1	1.005	1.014
2014–2015	0.998	0.951	1.005	0.993	0.949
2015–2016	0.973	1.036	0.986	0.986	1.007
2016–2017	0.977	1.011	1.006	0.971	0.988
2017–2018	0.976	1.02	1.006	0.97	0.995
2018–2019	1.022	0.955	1.002	1.02	0.976
Average	0.997	0.984	1.005	0.992	0.982

3.3 Analysis of spatiotemporal differences

By measuring the green transformation efficiency of the three major urban agglomerations in China from both static and dynamic perspectives, it can be seen that there are significant differences in the green transformation efficiency of the three major urban agglomerations. At the same time, within each urban agglomeration area, there are differences in the green transformation efficiency of the same city at different times and different cities at the same time. By drawing spatiotemporal evolution maps of green transformation in urban agglomerations in 2011, 2015, and 2019, the spatiotemporal differences in the efficiency of green transformation in the three major urban agglomerations in China are obtained Figure 6.

(1) There is a significant difference in the efficiency of green transformation among different cities within urban agglomerations. From a regional perspective, each city exhibits different green transformation efficiency. In the BTH, in addition to mature cities such as Beijing and Tianjin, there are also resource-based cities like Cangzhou

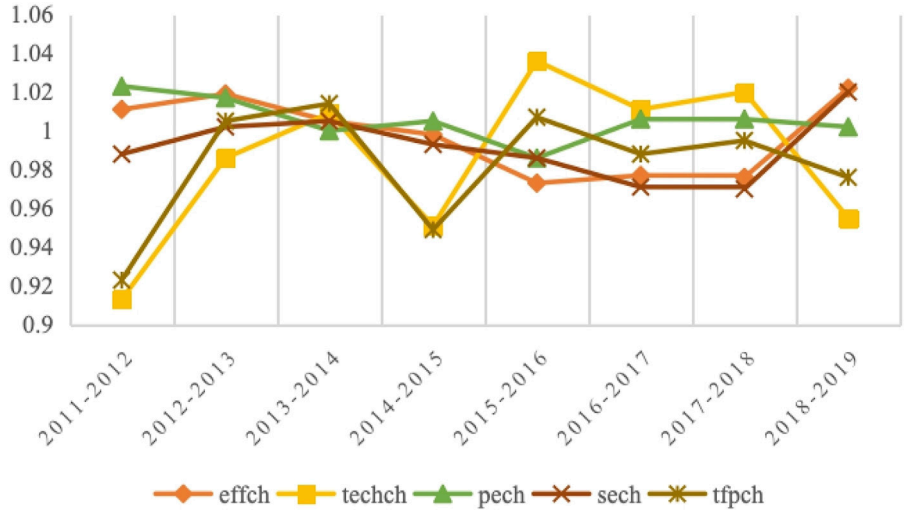


FIGURE 4
Dynamic efficiency and decomposition of green transformation in three major urban agglomerations in China from 2011 to 2019.

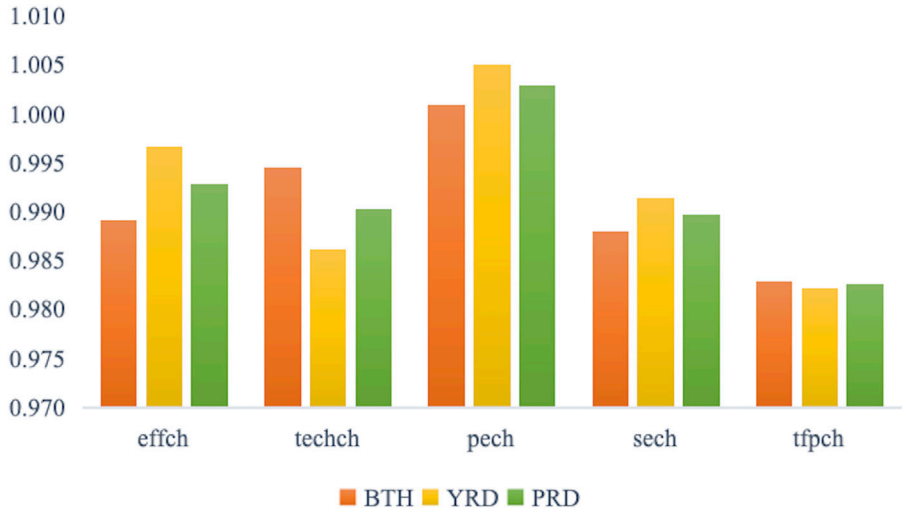


FIGURE 5
Malmquist index results and decomposition of three major urban agglomerations in China from 2011 to 2019.

that have achieved good results in green transformation. Since the official proposal of the "12th Five Year Plan" to promote the integrated development of BTH and create the capital economic circle, Beijing and Tianjin have been important engines for the coordinated development of the BTH, playing an important role in the fields of economy, healthcare, education, transportation, etc. As an advantageous resource-based city, Cangzhou City has issued multiple policy documents since 2011, focusing on regional characteristic industries, seizing opportunities for green transformation and development, guiding relevant industry enterprises to implement energy-saving technology upgrading and transformation, improving energy efficiency levels, and promoting the green and low-carbon transformation and development of traditional industries. In the YRD, besides mature cities such as Shanghai, Suzhou, and Hangzhou, there are also resource-based cities such as Ma'anshan and Tongling that have good green transformation effects. It is worth mentioning that Nanjing, as an economically advantageous city in the YRD, has a relatively unsatisfactory green transformation effect. The backward technological progress is the main reason for the decline in the comprehensive efficiency of green transformation in China's urban agglomerations. Therefore, in the future, Nanjing should increase research and development, invest in technology, and allocate financial resources reasonably to promote the green transformation of the city. At the same time, there are currently 6 cities in the



FIGURE 6
Spatial and temporal changes of green transformation efficiency of BTH, YRD and PRD in 2011, 2015, and 2019.

YRD with green transformation efficiency values below 0.7. The economic development level of these cities is relatively low, and there is significant redundancy in the investment of capital and labor, so the level of green transformation is relatively low. In the PRD, except for Huizhou and Dongguan, the green transformation efficiency of other cities is above 0.7. The overall green transformation situation of the PRD is good, and the internal differences are not significant. The PRD has always relied on the developed tertiary industry to achieve rapid economic growth, with a relatively light industrial structure, intensive innovation factors, and pursuit of green development. Therefore, the overall level of green transformation in the PRD is relatively high. From this, it can be seen that there may be significant differences in green transformation strategies among different cities. Some cities actively respond to the development direction of national green transformation, striving to achieve economic growth while ensuring environmental sustainability, while some cities pay more attention to economic growth and neglect the protection of the ecological environment, which cannot fully achieve DEA effectiveness, Some cities also have low output efficiency due to excessive emphasis on ecological security and significant constraints on economic development. In summary, the reasons for the low efficiency of green transformation in different cities are heterogeneous.

(2) There are significant differences in the efficiency of green transformation among the three major urban agglomerations. From a regional perspective, it can be concluded that the overall green transformation efficiency of the three major urban agglomerations varies greatly, and each urban agglomeration has different characteristics in green transformation. In terms of vertical development trend, the green transformation efficiency of China's three major urban

agglomerations showed an overall trend of first increasing and then decreasing from 2011 to 2018. However, it achieved a slight rebound in 2019, with significant fluctuations in the PRD and YRD, while the trend of changes in the BTH was not significant; In terms of horizontal development differences, the green transformation level of the three major urban agglomerations is ranked from high to low in the PRD, the YRD, and the BTH. The green transformation efficiency of the PRD and the YRD is similar, but they are significantly higher than the BTH. This result is also reflected in the research of other scholars or institutions, such as the "National New Urbanization Report 2016". The *per capita* GDP of the PRD is 105,000 yuan, ranking first in the national urban agglomeration. The population agglomeration continues to increase, innovative talents continue to be introduced, and the population age structure continues to exhibit the overall characteristics of "low at both ends, high in the middle". It has a good "population dividend" and "talent dividend". The PRD has been leveraging the innovative research and development capabilities of Guangzhou and Shenzhen, as well as Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen Zhaoqing and other places have the advantage of a complete industrial chain to create advanced industrial clusters; The YRD covers multiple provinces and has been a prosperous place since ancient times. The overall advantages of the urban agglomeration are obvious, and regional development is coordinated and balanced. All dimensions demonstrate comprehensive and comprehensive strength. In addition to maintaining a consistent leading advantage in Shanghai, Hangzhou, Nanjing, and Suzhou, Ningbo, Wuxi, Hefei, Changzhou, and Nantong have also rapidly emerged as core cities, with their engine role constantly increasing and their economic aggregate ranking first, forming a regional economic pattern with complementary advantages and high-quality development. At the same time, the YRD is also a livable place. Jiangsu and Zhejiang provinces have consistently ranked among the top in terms of greenery in the country, with good air quality and a high level of green development efficiency; The BTH has always relied on the two major cities of Beijing and Tianjin to drive the development of other small and medium-sized cities in Hebei Province. Hebei Province is an industrial province with high energy consumption, high pollution, and high emissions as the main characteristics of industrial development. The industrial structure is unreasonable, the pollutant emissions are large, and energy consumption ranks among the top in the country. The emissions of pollutants such as smoke, smoke, and sulfur dioxide have long been ranked first or second in the country. Therefore, the green transformation efficiency of the BTH is relatively low. On the one hand, it may be due to the ineffective implementation of the green transformation concept, and many traditional industries have not undergone timely transformation and upgrading, resulting in slow development of the green industry; On the other hand, Hebei Province is facing many limitations in technology, funding, talent, and other aspects. At the same time, it is also facing the dilemma of transferring polluting enterprises from Beijing, which has made the transformation of many enterprises very difficult and has not yet explored a mature environmental protection path. Therefore, the level of green transformation is still at a relatively low level, and the overall efficiency of green transformation is relatively low.

(3) There is little difference in the efficiency of green transformation among the three major urban agglomerations in terms of time dimension. Compared with the difference in green transformation efficiency of urban agglomerations in the spatial dimension, the difference in the temporal dimension is relatively small. The difference in efficiency values among the 48 cities in the three major urban agglomerations during the five-year period does not exceed 0.2. At the same time, from a dynamic perspective, technological progress is the main driving factor for improving the efficiency of green transformation in urban agglomerations. The change in total factor productivity depends on the combined effect of the technical efficiency change index and the technical progress index. Based on the decomposition results of the Malmquist index at different periods, it can be concluded that the impact of technological progress changes on total factor productivity is greater than that of technological efficiency changes. The trend of changes in total factor productivity is almost identical to that of technological progress, but it does not overlap because the impact of changes in technological efficiency on total factor productivity offsets some of the impact of changes in technological progress on total factor productivity. From this, it can be seen that the change in the technological progress index has a much greater impact on the efficiency of green transformation in urban agglomerations than the impact of technological efficiency on the efficiency of green transformation in urban agglomerations. This indicates that the technological change index mainly affects the changes in the efficiency of green transformation in urban agglomerations.

(4) The efficiency of green transformation in the three major urban agglomerations is affected by environmental constraints. The impact of environmental factors on cities is mainly reflected in the differences in efficiency values before and after adjustment, which are essentially influenced by economic development, energy consumption, and technological investment. After excluding the impact of environmental variables, the efficiency values of most cities have improved. The overall efficiency of green transformation after the adjustment has improved compared to before, indicating that environmental factors at this stage have a inhibitory effect on the green transformation efficiency of urban agglomerations. Although this effect is not significant, it is still necessary to continuously optimize the urban environment to promote the green transformation of urban agglomerations. In addition, there are also some non quantitative environmental factors, such as geographical location, cultural differences, differences in consumer attitudes, and policy influences. However, these factors cannot be quantified, so they are not reflected in environmental variables. These factors are also the reason for the differences in the efficiency of urban green transformation after adjusting for input variables.

TABLE 8 Regression results of Tobit model.

Impact factors	Regression coefficient	Standard error	Z statistics	P Statistics
ISU	0.451***	0 .001	2.99	0.002
GIL	0.522***	0.113	3.09	0.000
ERI	−0.0453**	0.035	−2.45	0.037
IC	0.377**	0.275	4.63	0.026
FDI	−0.0326***	0.064	−2.65	0.002
Constant	1.099***	0.529	20.76	0.000
LR = 51.05	Log likelihood = 16.791372	Prob>=chibar2 = 0.000***		

Note: ***, ** and * indicates the 1%, 5% and 10% significance level respectively.

3.4 Analysis of spatiotemporal differences

(1) Regression results

Using the efficiency value obtained in the third stage as the dependent variable and incorporating the aforementioned explanatory variables, the Tobit regression model was used to obtain empirical results as shown in Table 8.

It can be seen that the LR test result is 51.5, Prob>=chibar2 = 0.000, which is significant at the 1% significance level, indicating that the model setting is reasonable and there is a significant individual effect. The upgrading of industrial structure, level of green innovation intensity of environmental regulation, infrastructure construction, and degree of openness to the outside world are all important factors that affect the efficiency of green transformation in urban agglomerations.

Firstly, the impact coefficient of industrial structure upgrading on the efficiency of green transformation in urban agglomerations is positive and significant at the 1% significance level, indicating that the upgrading of industrial structure is conducive to promoting green transformation in urban agglomerations. On the one hand, the industrial structure is becoming more rational. With the continuous advancement of digital technology, the pillar industries of cities should shift more from labor-intensive and capital intensive industries to technology intensive and knowledge intensive industries. On the other hand, the industrial structure is more effective, eliminating and improving inefficient industries, vigorously promoting and developing efficient industries, promoting the integration and coordination of upstream and downstream industries, and forming an intelligent, green, and efficient industrial system.

Secondly, the impact coefficient of green innovation level on the efficiency of green transformation in urban agglomerations is positive and significant at the 1% significance level, indicating that the improvement of green innovation level is conducive to promoting green transformation in urban agglomerations.We must vigorously promote green technology innovation, leverage the empowering role of digital technology, coordinate economic development and environmental protection, and achieve efficient flow of production factors. At the same time, we should actively promote international cooperation in the field of technological innovation, and in the new context of the “dual carbon” goal, promote the continuous reduction of energy consumption per unit product, accelerate the improvement of the contribution rate of various new clean energy sources, and reduce the use and dependence on fossil fuels through technological progress.

Thirdly, the impact coefficient of environmental regulation intensity on the efficiency of green transformation in urban agglomerations is negative and significant at the significance level of 5%, indicating that an increase in environmental regulation intensity will slightly inhibit the green transformation of urban agglomerations. This may contradict our understanding, but in reality, in order to prevent further deterioration of the ecological environment, the government has issued relevant policy documents and adopted environmental regulation measures such as pollution limit and traffic control to protect the urban environment. However, at the same time, overly tough environmental regulatory measures often hinder the further development of the city’s economy, causing the city to fall into a cycle of resource curse. So if we want to truly achieve the green transformation of urban agglomerations, we should consider more from the perspective of technological progress and industrial upgrading, rather than blindly implementing environmental regulations. However, in order to achieve the goal of green transformation of development mode and high-quality economic development, it is feasible and meaningful to temporarily sacrifice short-term economic growth in some cities with severe environmental damage and low resource carrying capacity to achieve long-term environmental sustainable development. Because the intensity of environmental regulations has a relatively small impact on the efficiency of urban green transformation, the degree of inhibition on urban green transformation is relatively low.

Fourthly, the impact coefficient of infrastructure construction on the efficiency of green transformation in urban agglomerations is positive and significant at the significance level of 5%, indicating that the improvement of infrastructure construction is conducive to promoting the green transformation of urban agglomerations. The Ministry of Housing and Urban Development and the National Development and Reform Commission issued the “14th Five Year Plan” for national urban infrastructure construction in July this year, which mentioned the need to “accelerate the construction of new urban infrastructure and promote the transformation and development of urban intelligence”. With various policy documents raising higher requirements for urban development, the improvement of urban infrastructure is conducive to promoting cities to better absorb and utilize the funds, information, technology, talents and other elements

TABLE 9 Robust test results.

Impact factors	Regression coefficient	Standard error	Z statistics	P Statistics
ISU	0.549***	1.862	3.06	0.003
GIL	0.647***	0.278	2.87	0.002
ERI	−0.025**	0.233	−2.69	0.042
IC	0.543**	0.035	5.02	0.019
FDI	−0.051***	0.187	−2.47	0.004
Constant	6.826***	1.943	25.22	0.003
LR = 70.32	Log likelihood = 24.673496	Prob>=chibar2 = 0.000***		

Note: ***, ** and * indicates the 1%, 5% and 10% significance level respectively.

required in the process of urban development, and creating a new pattern of joint construction, governance, and sharing. At the same time, accelerating the construction of new urban infrastructure is also beneficial for cities to prioritize the development of emerging technology industries such as photovoltaic power generation, digital technology, and new energy, enabling cities to continuously move towards the direction of "smart cities".

Fifth, the coefficient of influence of the degree of openness on the efficiency of green transformation in urban agglomerations is negative and significant at the 1% significance level, indicating that an increase in openness will slightly inhibit the green transformation of urban agglomerations. With the improvement of the degree of opening-up to the outside world, foreign investment in urban industries is more concentrated in labor-intensive or capital intensive high energy consumption and high pollution industries, and its positive effect on the management experience and technological progress brought by the city is far less than the negative impact on the city's environmental pollution. In order to avoid the phenomenon of "pollution shelters", local governments need to screen the "green" level of foreign direct investment, strictly implement environmental protection access, raise the environmental access threshold for foreign direct investment, and fully leverage the technological advantages and spillover effects of foreign direct investment in environmental governance.

(2) Robust test

This article adopts the method of compressing sample data to verify the robustness of the results obtained. According to the results in Table 9, it can be seen that industrial structure upgrading, green innovation level, environmental regulation intensity, infrastructure construction, and degree of openness are important factors affecting the efficiency of green transformation in urban agglomerations, and the direction and degree of influence have not changed significantly, Therefore, to some extent, it indicates that the results obtained in this article have good robustness.

4 Discussion and conclusions

4.1 Discussion

(1) From a static perspective, the overall efficiency of green transformation in the three major urban agglomerations is at a high level, but not all have reached "DEA effectiveness". Among the 48 cities in the 9 year cycle, the overall level of green transformation in the three major urban agglomerations is relatively high, but from a time perspective, it shows a downward trend overall. Overall, the PRD is known for its green development, with the highest average efficiency value of green transformation, followed by the YRD. The level of green transformation has significantly increased since 2018, while the BTH has the lowest level of green transformation. It promotes the coordinated development of the urban agglomeration with Beijing and Tianjin as the centers, but the two cities' development is dominant, but they have not played a good agglomeration effect and central radiation effect, Most cities in Hebei Province have performed poorly in green transformation.

(2) From a dynamic perspective, technological progress is the main driving factor for improving the efficiency of green transformation in the three major urban agglomerations. Based on the specific decomposition of the Malmquist index in different periods, when the technological progress index decreases or rises, total factor productivity will also experience the same decrease or increase. The trend of change in total factor productivity is almost identical to that of technological progress, but does not overlap. The reason is that the impact of changes in technological efficiency on urban transformation efficiency offsets some of the impact of changes in technological progress, The trend of the efficiency of green transformation in urban agglomerations almost entirely depends on the change index of technological progress.

(3) From the perspective of spatiotemporal differences, there are significant differences in the spatiotemporal characteristics of green transformation among the three major urban agglomerations. In terms of spatial dimensions, there are significant differences in the efficiency of green transformation between different cities within urban agglomerations and among the three major urban agglomerations. There are significant differences in green transformation strategies among different cities, and the reasons for the low efficiency of green transformation in different cities are heterogeneous. Overall, the PRD has been leveraging the innovative research and development

capabilities of Guangzhou and Shenzhen, as well as the advantages of complete industrial chains in cities such as Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen, and Zhaoqing, to create advanced industrial clusters; The YRD covers multiple provinces and has been a prosperous place since ancient times. The overall advantages of the urban agglomeration are obvious, and regional development is coordinated and balanced, demonstrating comprehensive strength in all dimensions; The BTH has always relied on the two major cities of Beijing and Tianjin to drive the development of other small and medium-sized cities in Hebei Province. Its level of green transformation is lower than that of the PRD and the YRD. On the one hand, the green transformation concept in Hebei Province has not been effectively implemented, and many traditional industries have not undergone timely transformation and upgrading, resulting in slow development of the green industry There are many restrictions on talent and other aspects, while also facing the dilemma of transferring polluting enterprises from Beijing, and a mature path for environmental protection has not yet been explored. Compared with the differences in green transformation efficiency of urban agglomerations in the spatial dimension, the differences in time dimension among the three major urban agglomerations are relatively small, but they are all affected by environmental suppression. Although this impact is not significant, it is still necessary to continuously optimize the urban environment in order to promote the green transformation of urban agglomerations.

(4) From the perspective of influencing factors, government led factors and objective environmental factors jointly affect the green transformation efficiency of the three major urban agglomerations. Industrial structure upgrading, green innovation level, environmental regulation intensity, infrastructure construction, and degree of openness are all important factors that affect the green transformation efficiency of urban agglomerations. Among them, industrial structure upgrading, green innovation level, and infrastructure construction can promote the green transformation of urban agglomerations, and the degree of influence of the three is not significantly different; The intensity of environmental regulations and the degree of openness to the outside world will inhibit the green transformation of urban agglomerations, with a small coefficient of impact and a low degree of inhibition. From this, it can be seen that if we want to truly promote the green transformation of urban agglomerations, we should focus on three main factors: industrial structure upgrading, green innovation level, and infrastructure construction. At the same time, we should avoid overly tough environmental regulatory measures and control and screen the "green environmental protection" level of foreign direct investment.

(5) There are still the following aspects that need to be further studied in this article: firstly, the indicator system needs to be improved. This article currently constructs a green transformation evaluation system for urban agglomerations based on five aspects: economic growth, industrial transformation, resource saving, environmental governance, and improvement of livelihood. In the future, with the continuous deepening and improvement of the green transformation concept, a more comprehensive green transformation evaluation system can be constructed, and the selected indicators can be measured from multiple dimensions and aspects. Moreover, the selection of input-output indicators for efficiency evaluation in this article was also based on literature review and selection. Although statistical methods were also used to assist in screening and avoid some subjective factors, there may still be some biases in the evaluation results. Another thing is that the sample size needs to be enriched. This article selects the three most mature and well-developed urban agglomerations in China from 2011 to 2019 as research samples. In the future, more urban agglomerations can be studied, and with the passage of time and the improvement of data, the time span of the sample size will be longer, improving the credibility of the research results. Finally, the research methods need to be supplemented. In the future, in-depth analysis can be conducted using methods such as case analysis, policy evaluation, and spatial econometrics. Research methods from econometrics, geography, and public management can be introduced into the research, in order to enrich the relevant theories and practices in the field of urban transformation.

4.2 Conclusions

Based on the dynamic and static evaluation of the green transformation of the three major urban agglomerations and the analysis of spatiotemporal differences, as well as the empirical analysis of the factors affecting the efficiency of green transformation, and based on the actual development situation of the three major urban agglomerations in China, relevant policy recommendations are given from the following dimensions:

(1) Establish a concept of urban agglomeration development that combines overall improvement and internal collaboration. As the regional pattern shifts from "administrative region economy" to "urban agglomeration economy", the central government should quickly adapt to the development model dominated by urban agglomeration units. In terms of development philosophy, not only consider the overall economy, innovation, synergy, green and people's livelihood quality of urban agglomerations as important decision-making variables, but also take the construction of close and balanced urban connections and the creation of more spatial spillover windows as key performance indicators, truly promoting the development of urban agglomerations from "independent governance" to "shared governance". Pay attention to the differences between urban agglomerations and implement policies according to local conditions. Focus efforts on solving the bottleneck problems in areas such as economic operation, innovation driven, coordinated development, green transformation, people's livelihood sharing, and intercity collaboration based on the heterogeneity of structural sources and driving forces. The BTH should establish a global awareness, establish a

collaborative mechanism to promote green transformation, comply with the policies of carbon peaking and carbon neutrality, and create a green environment, industry, and financial circulation system; The YRD should leverage its consistent industrial and ecological advantages, emphasize spatial linkage development, deepen the layout of efficient development in economically developed cities such as Shanghai and Suzhou, and promote cooperation within the urban agglomeration; The PRD should fully utilize its unique ecological and geographical advantages, establish a unified green development system in conjunction with Hong Kong and Macau, inject technological innovation impetus into green development, and improve the network of central and peripheral urban agglomerations.

(2) Strengthen the network system of urban agglomerations, avoid conflicts between cities, fully leverage the coordination and promotion role of urban agglomerations, and achieve the synergy of "1 + 1>2″in cities. Cities are the foundation of urban agglomerations, and urban agglomerations are an organic combination of cities. In the process of promoting the green transformation of urban agglomerations, adhere to the policy of overall development of urban agglomerations and avoid elevating individual cities and ignoring macro layout. Simultaneously promoting the optimization of urban spatial structure, functional improvement, and quality improvement, integrating public services, and enhancing the resilience of the city. At the internal level of urban agglomerations, major urban agglomerations should strictly follow the development plans formulated by local governments or even the state, requiring internal cities to closely align with their functional positioning, fully leverage comparative advantages, and actively build a reasonable division of labor, complementary functions, and staggered development pattern for urban agglomerations. Especially for small and medium-sized cities, fully utilize the "scale borrowing" effect, promote their own development level by taking on the advantageous resources of core cities, thereby narrowing the development gap with core cities and strengthening the internal coordination of urban agglomeration development.

(3) Encourage green technology innovation and accelerate the upgrading of industrial structure. At the national level, continue to improve the collaborative innovation layout at the scale of urban agglomerations, continuously reduce the circulation cost of innovation factors between cities through building industrial technology alliances, joint research and development, improving transportation networks, and reforming institutional supply, thereby comprehensively enhancing the collaborative innovation capacity of urban agglomerations. Eliminate and improve inefficient industries, vigorously promote and develop efficient industries, promote the integration and development of upstream and downstream industries, and promote synergy between industries, forming an intelligent, green, and efficient industrial system. Give full play to the empowering role of digital technology, promote efficient and green application of technology, achieve efficient flow of production factors, and actively promote international cooperation in the field of technological innovation. Establish an intelligent and efficient energy system based on clean energy. Improve the level of green innovation, promote the continuous reduction of energy consumption per unit product, accelerate the contribution rate of various new clean energy sources, and reduce the use and dependence on fossil fuels through technological progress. Strengthen and optimize regional cooperation networks through scale restructuring, form regional adjacency spatial connections and higher-level economies of scale through spatial forms such as urban agglomerations, metropolitan areas, national level new areas, and global urban areas, creating a good situation of complementary advantages, win-win cooperation, and coordinated development between regions, and constructing a new model for the development of national networked spatial connections.

(4) Moderate environmental regulation and dual benefits of economic and environmental protection. Coordinate the relationship between economic growth and environmental protection, and pay attention to the selection of environmental regulation policy tools. When implementing environmental regulations, the government should pay attention to the coordination between objectives and the rationality of the selection of regulatory measures, focus on sustainable economic development, follow natural laws, and not exceed the environmental carrying capacity. Pay attention to the appropriateness and rationality of environmental regulations. Modernity requires environmental regulations to be moderate in degree, neither too lenient to effectively solve environmental problems, nor too strict to hinder economic and social development. This means that when formulating environmental regulatory policies, it is necessary to fully consider factors such as resource endowments, industrial structure, and development stages in different regions, and formulate regulatory measures tailored to local conditions. At the same time, it is necessary to adjust regulatory efforts in a timely manner based on the severity and urgency of environmental issues, ensuring that environmental regulations are in line with economic and social development. Rationality requires environmental regulations to be scientific, fair, and effective in terms of content and methods. The government should develop reasonable environmental standards, emission limits, and penalty measures based on scientific environmental risk assessment and prediction. It is necessary to strengthen environmental monitoring and regulatory capacity building to ensure the effective implementation of environmental regulatory policies.

(5) Guide foreign direct investment and attach importance to green and low-carbon areas. The government should deeply implement the Foreign Investment Law, strengthen the promotion and protection of foreign investment, continuously optimize the environment for foreign investment, and effectively avoid the formation of "pollution shelters". Emphasis should be placed on encouraging foreign investment in areas such as new energy, digital technology, innovation and demonstration applications of green and low-carbon key technologies. To promote economic growth through the "income effect" mechanism, it is necessary to establish a negative list of foreign investment, implement entry barriers for foreign direct investment, correctly guide the flow of foreign

investment, ensure that foreign investment conforms to national strategies and industrial development directions, promote the improvement of foreign investment quality, improve foreign investment layout, fully utilize foreign investment resources, and enhance the efficiency of foreign investment utilization. Strongly encourage foreign companies to participate fairly in the formulation and revision of relevant technical specifications, and also encourage foreign investment to engage in research and development of energy-saving and emission reduction technologies. In addition, actively promote foreign companies to participate in relevant international standard certification work, and encourage foreign-invested enterprises to become "leaders" in the green and low-carbon field.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

XM: Funding acquisition, Supervision, Writing–review and editing. ZL: Conceptualization, Data curation, Methodology, Software, Visualization, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Research on the impact of green insurance on regional environmental quality: evidence from China

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Green insurance (*GI*), as an innovative product integrating environmental protection and the financial sector, not only contributes to improving regional environmental quality (*EQ*) but also enhances corporate environmental risk management and awareness, driving the flourishing development of green finance and the environmental protection industry. Therefore, understanding the relationship between *GI* and *EQ* is crucial. This article delves into the mechanisms through which *GI* influences *EQ*, proposing a hypothesis that suggests an inverted "U" shape impact. Subsequently, based on panel data from 30 provinces in China spanning from 2000 to 2021, nonlinear regression models and threshold regression models were constructed to test the hypothesis. The research findings indicate: (1) Results from the fixed-effects regression model demonstrate that the impact of *GI* on China's *EQ* follows an inverted "U" shape. (2) Results from the threshold regression model also reveal an inverted "U" shape impact of *GI* on China's *EQ*, with a threshold value of 2.196. (3) Economic level and industrial structure exhibit significant inhibitory effects on *EQ* improvement. Technological level and environmental regulations demonstrate notable promotional effects. Population size shows no significant impact on *EQ* improvement. The study identifies a nonlinear effect of *GI* on *EQ* improvement, surpassing existing linear effect research, deepening the understanding of its impact on *EQ*, and contributing to the enhancement of regional *EQ*.

KEYWORDS

green insurance (GI), environmental quality (EQ), an inverted "U" shape, threshold regression model, China

1 Introduction

In recent years, environmental pollution has emerged as one of the most pressing global challenges. Taking air pollution as an example, the 2023 Global Air Quality Report released by the International Energy Agency revealed that only seven countries worldwide met the World Health Organization's PM2.5 guideline standards in 2023. A staggering 92.5% of countries and regions fell short of these standards (Dimitroulopoulou et al., 2023). Green insurance (*GI*), as an innovative product merging environmental protection with the financial sector, offers a novel avenue for enhancing environmental quality (*EQ*) (Hu et al., 2023). Therefore, this study aims to illuminate the impact of *GI* on regional *EQ*, unraveling its underlying mechanisms in environmental governance. It seeks to provide insights and inspiration for the development of regional green finance and the enhancement of *EQ*.

In recent years, China has experienced rapid economic growth, marked by swift strides in marketization, industrialization, and internationalization. However, escalating environmental pollution has emerged as a bottleneck hindering China's sustainable development. Furthermore, China's enormous population, rapid industrialization and urbanization, and export-oriented economy have propelled it to become one of the world's largest carbon emitters. Nevertheless, the Chinese government has actively promoted ecological civilization construction in recent years, implementing a series of environmental protection policies and measures. Lastly, China stands as a significant testing ground for the development of green finance. In 2023, China's *GI* revenue reached 229.7 billion yuan, with payouts totaling 121.5 billion yuan, spanning various sectors including transportation infrastructure, clean energy, and wastewater treatment (Wen et al., 2024). In summary, China's environmental governance practices and the advancement of green finance wield significant influence and serve as exemplary models for global environmental protection endeavors.

To thoroughly investigate the impact of *GI* on regional *EQ*, this paper first constructs an *EQ* evaluation index system to conduct an in-depth assessment of the current *EQ* in China. Furthermore, through an in-depth research of the impact mechanisms of *GI* on *EQ*, the hypothesis is proposed that the impact of *GI* on China's *EQ* follows an inverted "U" shape. Subsequently, this paper uses panel data from 30 provinces in China from 2000 to 2021 to construct nonlinear panel regression models and threshold regression models to validate the proposed hypotheses. Finally, based on the research findings, recommendations for strategies to promote the improvement of China's *EQ* are put forward. Studying the impact of *GI* on regional *EQ* can provide a new theoretical perspective for the field of environmental economics. Deepen the understanding of the coordinated relationship between environmental protection and economic development. To provide support for building more effective environmental governance theories. On the other hand, this article intends to examine the inverted U-shaped nonlinear relationship between *GI* and *EQ*, which goes beyond the scope of traditional linear analysis. Deepening its understanding of the impact on *EQ* can provide scientific basis for government environmental governance. Promote the transformation of the economy towards a green and sustainable direction.

The significance of this study lies in the ambiguity surrounding the operational mechanisms of *GI* as an emerging tool for environmental protection. A comprehensive investigation into the impact of *GI* on *EQ* holds paramount importance. Moreover, empirical analysis of the relationship between *GI* and *EQ* can furnish governmental bodies with scientific grounds for formulating more precise environmental policies. Finally, by delving into the inverted *U*-shaped relationship between *GI* and *EQ*, this study aids in unveiling the latent mechanisms of *GI* in environmental governance, thereby offering valuable insights and inspiration for the development of green finance.

Compared to previous studies, the primary contribution of this research lies in its systematic exploration of the impact of *GI* on the *EQ* of Chinese provinces through the introduction of a threshold regression model. Furthermore, it substantiates the existence of an inverted *U*-shaped relationship. Additionally, this study accounts for the heterogeneity among Chinese provinces, robustly examining the validity of its findings, thus enhancing the credibility and persuasiveness of the research outcomes.

2 Literature review

With the continuous severity of global environmental issues, enhancing *EQ* has become a focal point of widespread attention in academic and policy domains. Regional *EQ* is influenced by various factors. Some studies have found that the production processes of heavy industry often generate large amounts of industrial solid waste, wastewater, and exhaust gases (Wang et al., 2023a). The production and use of fossil fuels also result in significant greenhouse gas emissions (Gillingham and Stock, 2018). Therefore, the industry structure dominated by heavy industry and the energy structure dominated by fossil fuels are important factors affecting regional *EQ*. On the other hand, advanced technological levels contribute to the improvement of clean technologies and resource utilization efficiency (Wang et al., 2024). Environmental protection policies enacted and enforced by the government directly impact the behavior of businesses and individuals (Wang et al., 2023b). Therefore, technological levels and environmental protection policies are crucial factors in enhancing regional *EQ*. In addition, some scholars have found that the increase in the level of urbanization is often accompanied by the rapid development of industrialization and extensive infrastructure construction, leading to increased emissions of pollutants and a decrease in regional *EQ* (Liang et al., 2019). However, other scholars have different findings, suggesting that urbanization improves the utilization of production factors, reduces resource waste, and lowers pollutant emissions (Li et al., 2022). Finally, a minority of scholars have delved into the impact of factors such as foreign direct investment (FDI) (Wang et al., 2023c), population mobility (Dhondt et al., 2012), and motor vehicles (Montag, 2015) on regional *EQ*.

GI, as an emerging insurance model, aims to enhance *EQ* through financial means (Mills, 2009). In recent years, numerous scholars have extensively researched the development and application of *GI*. Through theoretical analysis, many scholars have found that *GI* plays a positive role not only in strengthening enterprise environmental risk management (Yang and Zhang, 2022) but also in accelerating the layout of green industries (Mills, 2003) and promoting innovation in green technologies (Hu et al., 2023). It can continuously enhance public and societal environmental awareness (Brogi et al., 2022), guide the direction of social funds (Desalegn, 2023), and promote the improvement of regional *EQ*. On the other hand, a minority of scholars, through empirical research, have delved into the impact of *GI* on *EQ*. The research by Ning and other scholars indicates that *GI*, through flexible premium designs, incentivizes enterprises to adopt more environmentally friendly production methods, encouraging the reduction of pollution emissions (Ning et al., 2023). Studies by Hou and others indicate that enterprises purchasing *GI* allocate more funds to environmental protection projects (Hou and Wang, 2022). A limited number of scholars have delved into an empirical analysis to further investigate the impact of *GI* on environmental pollution. Scholars such as Ning have uncovered that the differentiated premium design of *GI* serves as an incentive for

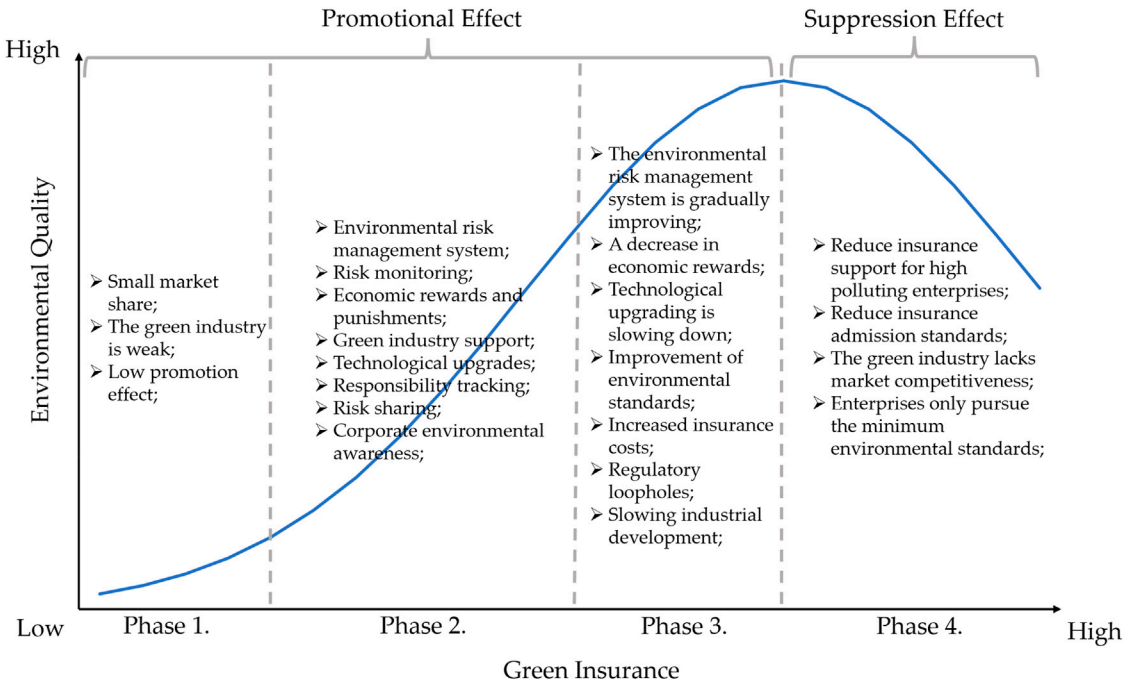


FIGURE 1
Analysis chart of impact mechanism.

enterprises to adopt more environmentally friendly production methods, thereby exerting a promoting effect on the enhancement of regional *EQ* (Ning et al., 2023). The research conducted by Hou and others reveals that enterprises purchasing *GI* allocate more funds to environmental construction, leading to a reduction in pollution emissions (Hou and Wang, 2022). However, divergent conclusions have been drawn by some scholars who argue that *GI* may impede the improvement of *EQ*. Lu and collaborators found that an excessive reliance on *GI* could diminish the proactive innovation in green technologies by enterprises, ultimately hindering long-term benefits for the enhancement of regional *EQ* as companies merely satisfy minimum environmental standards (Lu et al., 2022). In their study focused on China's environmental protection industry, Yang and team discovered a relatively modest impetus of *GI* on the environmental protection industry and a limited impact on the improvement of *EQ* (Hou and Wang, 2022).

In conclusion, the study of the impact of *GI* on *EQ* is still in its infancy as an emerging field. Existing research outcomes suggest a linear relationship between *GI* and *EQ*, yet discrepancies and contradictions persist among these findings. Some studies assert the positive effects of *GI*, while others hold opposing views. This paper aims to employ threshold regression and nonlinear models to examine the inverted *U*-shaped relationship, thereby elucidating the aforementioned contradictions. By transcending traditional linear analyses, this research deepens our comprehension of how *GI* influences *EQ*. It provides a more nuanced and profound perspective for the study of *GI* and *EQ*, ultimately empowering governments to tailor and adjust *GI* policies with greater precision. This strategic approach maximizes the positive impact on the environment, fostering sustainable regional development.

3 Influencing mechanism and hypothesis

GI plays a crucial role in improving regional *EQ*, and its impact on *EQ* varies at different stages, as shown in Figure 1.

First is the initiation stage of the promotion effect. In the early introduction of *GI*, regional society and government have a low level of attention to *EQ* issues. The development of the green industry is weak, and businesses have a limited understanding of *GI*. This leads to a small market share for *GI* and a lower promotion effect on *EQ* (Zhu et al., 2023).

Second is the expansion stage of the promotion effect. As *EQ* issues receive widespread attention from society and government, the *GI* market gradually expands, and the *EQ* promotion effect of *GI* significantly increases. This includes the improvement of enterprise environmental risk management systems, risk monitoring, economic incentives and penalties, technological upgrades and applications, environmental responsibility tracking, risk sharing, support for green industries, etc., effectively promoting a rapid improvement in regional *EQ*. Moreover, with the increase in corporate information transparency and the emphasis on corporate environmental responsibility by society, companies begin to take voluntary environmental measures, accelerating the improvement of *EQ* (Rahmatiar, 2018).

Third is the slowing stage of the effect. As the *GI* market continues to expand, certain factors contribute to the gradual slowdown of the *EQ* promotion effect of *GI* (Lee and Fung, 2023). First, enterprise environmental risk management systems are becoming increasingly perfected, and pollution reduction measures that are relatively easy to implement have become widely adopted. Second, environmental standards are gradually

TABLE 1 Chinese *EQ* evaluation indicators.

Target indicator	Classification indicator	Specific indicator	Unit	Indicator attribute
Environmental quality	Environmental carrying capacity	Industrial waste water discharge	10 thousand tons	Negative
		Emissions of SO_2 in industrial waste gas	tons	Negative
		Emissions of nitrogen oxides in industrial waste gas	tons	Negative
		The amount of common industrial solid waste generated	10 thousand tons	Negative
		Emissions of nitrogen oxides from motor vehicles	tons	Negative
	Environmental governance level	Industrial waste water treatment facilities	sets	Positive
		Industrial waste gas treatment facilities	sets	Positive
		The amount of common industrial solid wastes utilized	10 thousand tons	Positive
		Investment in treatment of industrial pollution sources	100 million yuan	Positive

increasing, environmental incentive mechanisms are insufficient, and green technologies face bottlenecks, leading to rising environmental costs and a slowdown in the promotion effect. Third, the growth of the green industry is slowing, with the primary factor affecting green industry development no longer being a lack of funds but rather technological breakthroughs. Fourth, with the expansion of the *GI* market, market supervision may lag behind market changes, leading to regulatory loopholes in the *GI* market.

Fourth is the suppression effect stage. When the market share of *GI* reaches saturation, the promotional effect of *GI* transforms into a suppression effect. On one hand, as competition intensifies in the *GI* market and related regulations become stricter, insurance companies are compelled to raise environmental standards and reduce support for highly polluting enterprises (Wang et al., 2021). On the other hand, with the comprehensive expansion of the *GI* market, excessive reliance by the government, industry, and enterprises on the *EQ* promotion effect of *GI* leads to the government lowering environmental standards, the green industry lacking market competitiveness, and enterprises merely meeting the minimum environmental standards, resulting in a decline in *EQ* (Wang et al., 2014).

In summary, this paper proposes a research hypothesis: In China, the impact of *GI* on *EQ* follows an inverted "U" shape. There is a positive relationship up to a certain extent, but with the influence of various factors, this relationship may reverse.

4 Methodology and data

4.1 Environmental quality evaluation

4.1.1 Evaluation index system of environmental quality

Since the 21st century, global environmental pollution issues have become more prominent. Different regions choose various environmental indicators for *EQ* assessments based on their specific circumstances. For example, air quality index, carbon emission index, noise pollution index, etc. Some scholars integrate multiple environmental dimensions such as atmosphere, water, soil, ecology, and noise to establish a comprehensive evaluation index, thereby conducting a comprehensive assessment of regional *EQ*. According to the analysis of the impact paths of *GI* on regional *EQ*, it can be observed that currently, *GI* in China primarily focuses on industrial pollutant emissions, with minimal impact on residential pollution (Shi et al., 2023). In light of the mentioned characteristics, this paper draws extensively upon the contributions of scholars such as Miao in the research field (Miao et al., 2016). Ultimately, nine specific indicators were selected to establish a comprehensive *EQ* evaluation index from the critical dimensions of regional environmental carrying capacity and environmental governance level. The detailed interpretation of these indicators is presented in Table 1.

4.1.2 Evaluation method for environmental quality

Evaluating regional *EQ* requires not only the establishment of an *EQ* evaluation index system but also the determination of weights for each indicator. In the academic realm, methods for determining indicator weights can be categorized into subjective and objective approaches. Subjective methods rely on personal judgment, such as expert scoring and the analytic hierarchy process (AHP). Objective methods, on the other hand, use data and mathematical models to determine weights, including the entropy method and principal component analysis. Objective weighting methods, relying on mathematical models and data analysis, are more scientific and objective, less susceptible to personal subjective views, and more flexible in dealing with complex issues and multi-criteria decision-making. Drawing on the research of scholars like Cheng, this paper applies the entropy method to further evaluate regional *EQ* (Cheng et al., 2023).

The entropy method is a mathematical approach used for multi-criteria decision analysis. It is primarily employed to determine the weights of each decision factor for a better understanding and evaluation of various alternative solutions. The steps in applying the entropy method include:

Step 1, data standardization processing. Standardize the data of each indicator in the *EQ* evaluation index. Ensure that the data for each indicator is within the same dimension and range of variation. The standardized processing formulas for positive and negative indicator data are shown in formula (1) and formula (2), respectively.

TABLE 2 Variable descriptions.

Variable		Variable definition	Symbol
Interpreted variable	Environmental quality	Evaluation results of environmental quality	*EQ*
Core explanatory variable	Green insurance	The proportion of environmental pollution liability insurance income to total insurance income	*GI*
Control variables	Economic scale	Per capita GDP	*PGDP*
	Population size	Total population	*TP*
	Industrial structure	Proportion of the secondary industry	*IS*
	Technology level	Unit GDP energy consumption	*TL*
	Environmental regulation level	Proportion of industrial pollution control investment completed to industrial value added	*ER*

$$x'_{ij} = \frac{x_{ij} - \min\left(x_j\right)}{\max\left(x_j\right) - \min\left(x_j\right)} \quad (1)$$

$$x'_{ij} = \frac{\max\left(x_j\right) - x_{ij}}{\max\left(x_j\right) - \min\left(x_j\right)} \quad (2)$$

Step 2, calculate the entropy value. Calculate the entropy value of each indicator in the evaluation index system using the formula (3). Among them, p_ij is the proportion of the *j*th data under indicator i, and N is the number of samples in the dataset. The entropy value reflects the uncertainty and information content of the indicator, and the larger the value, the higher the information uncertainty.

$$E_i = -\frac{p_{ij}\ln\left(p_{ij}\right)}{\ln\left(N\right)} \; p_{ij} = \frac{x'_{ij}}{\sum_{i=1}^{n} x'_{ij}} \quad (3)$$

Step 3, calculate the weights. Calculate the weight of the entropy value for each indicator, as shown in formula (4). Among them, k is the number of indicators.

$$w_i = \frac{1 - E_i}{k - \sum_{i=1}^{k} E_i} \quad (4)$$

Step 4, normalize weights. Normalize the calculated weights to ensure that the sum of weights for each indicator is 1.

4.2 Regression models construction

To test the hypothesis that the impact of *GI* on *EQ* in China follows an inverted "U" shape, this paper first introduces the quadratic term of the core explanatory variable to construct a nonlinear regression model. Secondly, borrowing from Hansen's method, a threshold regression model based on *GI* for *EQ* is constructed (Yi and Xiao, 2018).

4.2.1 Variable selection and data interpretation

Through a comprehensive review of existing research results on factors influencing *EQ*, we found a diverse range of factors affecting regional *EQ*, including economic, population, industrial, technological, energy, and policy factors. Combining the commonalities in the development of *EQ* across Chinese provinces, we systematically selected six key influencing factors, as shown in Table 2.

Interpreted variable: The *EQ* of various provinces in China is calculated based on the *EQ* evaluation index system constructed in the previous sections.

Core explanatory variable: The *GI* of various provinces in China is expressed by the proportion of environmental pollution liability insurance revenue to the total insurance revenue.

Control variables: (1) Selecting *per capita* GDP to reflect the regional economic development level. Regions with higher economic development levels may have more industrial activities and transportation, leading to increased emissions of pollutants such as exhaust gases and wastewater. Therefore, this indicator may decrease regional *EQ* (Lu et al., 2017). (2) Selecting total population to reflect the regional population level. Regions with large population concentrations may lead to higher levels of industrialization and urbanization, thereby increasing pollutant emissions. At the same time, the demand from a large population also drives more traffic and production activities, increasing pollutant emissions. Therefore, this indicator may decrease regional *EQ* (Li et al., 2019). (3) Selecting the proportion of the secondary industry to reflect regional industrial structure characteristics. The secondary industry, compared to the primary and tertiary industries, requires more production materials and may emit more pollutants. Therefore, this indicator may decrease regional *EQ* (Chen et al., 2021). (4) Selecting unit GDP energy consumption to reflect regional technological level. Advanced technological levels imply more efficient resource utilization, which can reduce fossil fuel consumption and even use clean energy. Therefore, this indicator may increase regional *EQ* (Mughal et al., 2022). (5) Selecting the proportion of investment in industrial pollution control to industrial value-added to reflect the level of environmental regulation. Reasonable environmental regulations can promote the upgrading of pollution control facilities by enterprises, reduce pollution emissions, and achieve improvement in regional *EQ* (Yang et al., 2018).

Considering the availability and completeness of the data, this paper selects relevant data from 30 provinces in China for the period 2000-2021 to investigate the relationship between *GI* and *EQ*. The dataset does not include data from the regions of Hong Kong, Macao, Taiwan, and Tibet. *GI* data is obtained from the annual "China Insurance Yearbook," while other data is collected from the annual "China Statistical Yearbook," "China Environmental Statistical Yearbook," and provincial statistical yearbooks. It is important to note that, to prevent the influence of non-stationarity of macro data on empirical results, all variables have been log-transformed. For missing data, we used either the mean imputation method or the nearest neighbor interpolation method for supplementation.

4.2.2 Nonlinear regression model (NRM)

This article uses a quadratic regression model to test the hypothesis that the impact of *GI* on China's *EQ* is an inverted "U" shape. The coefficients of the quadratic regression model bear an intuitive interpretation. The coefficient of the linear term variable signifies the slope of the linear relationship within the model, while the coefficient of the quadratic term variable reflects the concavity or convexity of the nonlinear relationship. This imparts a heightened level of intuitiveness and operability to the explication of the model outcomes. The underlying principle of the model unfolds as follows: when the coefficient of the quadratic term variable takes a negative value, the model manifests a inverted *U*-shaped form after the variable reaches a certain level. This configuration aligns with our conceptualization of an inverted *U*-shaped relationship, wherein the optimal *EQ* is attained when the *GI* level is moderate. Conversely, under excessively high or low *GI* levels, the *EQ* might experience a decline. A notably negative coefficient of the quadratic term variable indicates the presence of an inverted U-shaped relationship between *GI* and *EQ*.

To test the hypothesis that the impact of *GI* on *EQ* in China follows an inverted "U" shape, this paper introduces the quadratic term of *GI* (Haans et al., 2016). And introduce other variables that affect *EQ*, such as *PGDP*, *TP*, *IS*, *TL*, and *ER*. The complete nonlinear regression model for studying *EQ* is shown in Formula (5). In the Formula (5), *i* represents the *i*th province among the 30 provinces in China, and *t* represents the *t*th year from 2000 to 2021. For example, EQ_{it} represents the environmental quality level of province *i* in year *t*, and GI_{it} represents the green insurance level of province *i* in year *t*. Similarly, $PGDP_{it}$, TP_{it}, IS_{it}, TL_{it} respectively represent the *per capita* GDP, total population, industrial structure, technological level, and environmental regulation level of province *i* in year *t*.

$$ln\,EQ_{it} = \alpha_i + \beta_1 lnGI_{it} + \beta_2 lnGI_{it}^2 + \beta_3 lnPGDP_{it} + \beta_4 lnTP_{it} + \beta_5 lnIS_{it} + \beta_6 lnTL_{it} + \beta_7 lnER_{it} + \mu_{it} + \varepsilon_{it} + \delta_{it} \quad (5)$$

4.2.3 Threshold regression model (TRM)

To further test the hypothesis that the impact of *GI* on *EQ* in China follows an inverted "U" shape, this paper employs Hansen's proposed threshold panel model to analyze the influence of *GI* on *EQ* at different development stages. This paper constructs a regional environmental quality threshold regression model using *GI* as a threshold variable. The final model is shown in Formulas (6) and (7) (Lv and Xu, 2023). The meanings of each character in formulas (6) and (7) are consistent with those in formula (1). In addition, η represents the threshold value.

$$lnEQ_{it} = \alpha_i + \beta_1 lnGI_{it} + \beta_2 lnPGDP_{it} + \beta_3 ln\,TP_{it} + \beta_4 lnIS_{it} + \beta_5 lnTL_{it} + \beta_6 lnER_{it} + \mu_{it} + \varepsilon_{it} + \delta_{it}\ (lnGI \le \eta) \quad (6)$$

$$lnEQ_{it} = \alpha_i + \beta_1 lnGI_{it} + \beta_2 lnPGDP_{it} + \beta_3 ln\,TP_{it} + \beta_4 lnIS_{it} + \beta_5 lnTL_{it} + \beta_6 lnER_{it} + \mu_{it} + \varepsilon_{it} + \delta_{it}\ (lnGI > \eta) \quad (7)$$

The threshold regression model consists of two components: one capturing the linear relationship below the threshold and the other above the threshold. Such a model structure enhances the flexibility to depict the nonlinear impact of *GI* on *EQ*. It allows for modeling variations in *EQ* near the threshold. The pivotal aspect of the threshold regression model lies in the examination of the threshold. Through hypothesis testing on the threshold, it can be determined whether there exists a threshold for the impact of *GI* on *EQ*. This aids in comprehending at what level of *GI* the impact on *EQ* is optimized. The threshold regression model furnishes explanations for both stages below and above the threshold, enabling researchers to gain a clearer understanding of the mechanism through which *GI* affects *EQ*. Such interpretability holds practical guidance for policy formulation and operational practices.

5 Results and discussions

5.1 Descriptive statistical analysis

The results of the descriptive statistical analysis are shown in Table 3. The extreme values of the seven variables are relatively small, mostly within two digits, and each variable has a small skewness and a large kurtosis. This indicates that the sample data distribution is relatively symmetrical, but with heavier tails. In addition, the *p*-values of the JB statistics are all less than 0.05, rejecting the null hypothesis. There is sufficient evidence to conclude that the seven variables do not follow a normal distribution.

5.2 Unit root test

Unit root testing is a crucial step in time series analysis and is used to detect whether time series data exhibits non-stationarity. Non-stationary time series data can lead to potential issues in many statistical methods and models, making unit root testing essential for the accuracy and reliability of subsequent analyses. This paper employs LLC test, ADF test, and IPS test to conduct unit root tests on the selected variables, as shown in Table 4. The test statistics of the three unit root testing methods are significantly larger than the critical values, leading to the acceptance of the alternative hypothesis that the sequence is stationary.

5.3 Results and discussion of the nonlinear panel regression model

5.3.1 Results

In testing the hypothesis that the impact relationship between green insurance and environmental quality is an inverted "U" shape using a nonlinear panel regression model, it is necessary to determine whether to use a fixed effects model or a random effects model. These two models handle heterogeneity among individuals in panel data differently. Therefore, this paper employs the Hausman test method to test the fixed effects model against the random effects model. The results are shown in Table 5. The test results indicate a chi-square value of 57.98, with a corresponding probability value of 0.0000. Consequently, this research rejects the random effects regression model and tends to choose the fixed effects regression model.

TABLE 3 Descriptive statistical analysis results.

Variable	Mean	Std. Dev	Maximum	Minimum	Kurtosis	Skewness	JB [p.]
EQ	0.75	0.16	1.00	0.33	−0.56	−0.58	45.72 [0.000]
GI	6.74	1.44	9.69	4.04	−1.10	0.06	33.96 [0.000]
PGDP	3.85	3.05	18.40	0.27	2.62	1.42	405.4 [0.000]
TP	0.45	0.27	1.27	0.05	−0.22	0.68	52.57 [0.000]
IS	44.77	8.41	61.50	15.80	1.10	−1.00	141.0 [0.000]
TL	1.15	0.76	4.52	0.18	3.64	1.69	672.2 [0.000]
ER	0.40	0.36	2.85	0.01	12.07	2.77	478.0 [0.000]

TABLE 4 Unit root test results.

	IPS Test	ADF Test	LLC Test	Conclusion
EQ	−1.963***	4.847***	−4.745***	Stability
GI	−4.244***	4.936***	−7.621***	Stability
PGDP	−3.583***	2.395***	−9.316***	Stability
TP	−2.581***	7.029***	−6.229***	Stability
IS	−7.976***	10.325***	−9.005***	Stability
TL	−1.374***	5.272***	−1.903***	Stability
ER	−2.097***	6.175***	−3.111***	Stability

***$p < 0.01$.

TABLE 5 Hausman test results.

	Chi-sq. Statistic	Prob > chi2
Value	57.98	0.000

TABLE 6 Fixed effects regression results.

Variable	Coefficient
lnGI	0.305**
$lnGI^2$	−0.071***
lnPGDP	−0.212***
lnTP	0.247
lnIS	−0.170***
lnTL	0.121***
lnER	0.263***
R^2	0.893
Prob > F	0.0000

***p <0.01, ** p <0.05.

The results of the fixed effects regression model are shown in Table 6, with an *R-squared* equal to 0.893, indicating that the explanatory variables included in the model can effectively explain the variation in the dependent variable. The *p*-values corresponding to *lnGI*, $lnGI^2$, *lnPGDP*, *lnIS*, *lnTL*, and *lnER* are all less than 0.05, significantly affecting China's *EQ*. However, at a significance level of 10%, *TP* did not have a significant impact on *EQ*.

5.3.2 Discussion

The coefficient of *lnGI* on *lnEQ* is positive, with a value of 0.305, indicating that as the level of *GI* increases, the level of *EQ* also rises. The coefficient of $lnGI^2$ on *lnEQ* is −0.071, indicating that the impact of *GI* on *EQ* follows an inverted "U" shape. In the early stage of *GI* development, it can enhance the enterprise's environmental risk management system and establish a scientific environmental protection strategy. It can promote increased environmental investment by implementing economic incentives and penalties. Through risk monitoring mechanisms and responsibility tracking mechanisms, it encourages companies to actively fulfill their environmental responsibilities. It can share the risk of technological innovation, promote the upgrade and application of green technologies. Financial support can guide investment direction and support the stable and rapid development of the green industry. Therefore, *GI* can reduce pollution emissions and promote the improvement of regional *EQ*. On the other hand, as the level of *GI* development continues to rise, when the market share of *GI* reaches saturation, the promotional effect of *GI* transforms into an inhibitory effect. The main reasons are that with the continuous development of the *GI* level, market competition intensifies, and related regulations become more stringent, forcing insurance companies to raise environmental standards and reduce insurance support for highly polluting enterprises. Additionally, as the *GI* market fully unfolds, excessive reliance on the *EQ* promotion effect of *GI* by the government, industry, and enterprises leads to a lowering of environmental standards by the government, a lack of market competitiveness in the green industry, and companies merely meeting the minimum environmental standards. This results in a decline in *EQ*. Existing research findings on the impact of *GI* on *EQ* have yielded contradictory results. Some studies posit a positive effect of *GI* on *EQ*, while others hold a contrary perspective. For instance, Rizwanullah et al., based on linear regression analysis, found a positive impact of *GI* on the *EQ* of BRICS (Rizwanullah et al., 2022). Conversely, Ahmed et al., utilizing linear regression analysis as well, discovered a negative impact of *GI* on the *EQ* of the United States (Ahmed et al., 2022). Through the revelation of an inverted U-shaped relationship in this

study, not only can these conflicting results be elucidated, but it also expands the research perspective on the enhancement effects of *GI* on *EQ*. The discovery of such a nonlinear relationship provides a more profound and comprehensive understanding of *GI* research, offering insights into its nuanced impact on *EQ*.

Further calculations reveal that when the value of *GI* equals 8.567, the relationship between *GI* and *EQ* begins to show a turning point. That is, when *GI* is greater than 8.567, *EQ* decreases with the increase of *GI*. Spatial-temporal difference analysis of 30 provinces in China conducted in this study found that in 2016, the level of *GI* in Jiangsu Province first exceeded 8.567, followed by Beijing, Shanghai, Zhejiang, and Yunnan provinces. Combining with the development history of *GI* in China, we found that since the implementation of *GI* policies, the level of *GI* in China has continuously increased, growing from 4.42 in 2000 to 9.08 in 2021. In the initial stage, the introduction of *GI* effectively reduced pollutant emissions, leading to an improvement in regional *EQ*. However, the blind promotion of *GI* development has also brought a series of environmental pollution issues, inhibiting the improvement of *EQ*. Taking Jiangsu as an example. The *GI* and *EQ* of Jiangsu Province in 2000 were 4.41 and 0.466, respectively. With the continuous development of *GI*, *EQ* continued to rise, reaching the highest value of 0.768 by 2016. Then, Jiangsu Province's *EQ* declined continuously with the growth of *GI*. By 2021, Jiangsu Province's *GI* had grown to 9.13, and *EQ* had reduced to 0.658.

Analyze the impact of each control variable on EQ in detail. (1) The impact coefficient of PGDP on EQ is −0.212, indicating a significant inhibitory effect of PGDP on EQ. Currently, China's rapid economic growth relies predominantly on high-energy-consuming and pollution-intensive heavy industries and manufacturing. The development of these traditional industries often accompanies substantial energy consumption and environmental pollution emissions, leading to deteriorating *EQ*. Hence, the improvement of EQ in China exhibits a suppressing effect due to PGDP. Existing research outcomes on the influence of PGDP on Chinese EQ have yielded conflicting results. Some studies suggest a positive effect of PGDP on EQ, while others hold the opposite view. Song et al. found that, influenced by high-energy-consuming and high-emission industries, Chinese EQ declines with the growth of PGDP, consistent with the findings of this study (Song et al., 2020). However, Awan et al. focused on Shanghai and discovered that with economic development, an increase in *per capita* GDP leads people to be more inclined towards investing in environmental protection and improvement measures, thereby enhancing *EQ* (Awan and Azam, 2022). (2) The significant negative impact coefficient of IS indicates that for every increase of 1 unit in IS, EQ decreases by 0.17 units, demonstrating a notable inhibitory effect of IS on EQ. China's secondary industry primarily comprises industries such as manufacturing and heavy manufacturing, which often exhibit high energy consumption and pollution characteristics. With the increasing proportion of the secondary industry, the development of industries such as manufacturing may lead to significant energy consumption and emissions of environmental pollutants, thereby exerting adverse effects on *EQ*. Yin and Song conducted an empirical analysis on the impact of industrial structure on regional *EQ* in China. The results consistently indicate a decline in regional *EQ* with the increase in the proportion of the secondary industry, aligning with the conclusions of this study (Song et al., 2022; Yin et al., 2024). (3) The significant positive impact coefficient of TL indicates that for every increase of 1 unit in TL, EQ increases by 0.121 units, demonstrating a noteworthy promoting effect of TL on EQ. In recent years, China has witnessed rapid development and widespread adoption of renewable and clean energy technologies, reducing reliance on traditional fossil fuels, and consequently lowering carbon emissions and other pollutants, thereby benefiting *EQ*. Furthermore, China's advancements in production technology have continuously elevated resource utilization efficiency, reducing wastage and consumption of resources effectively. This has also led to a reduction in pollutant emissions during the production process, thereby alleviating environmental pressures. Villanthenkodath and Chishti respectively studied India and the BRICS economies, empirically analyzing the impact of technological levels on regional *EQ*. The results consistently demonstrate an improvement in regional *EQ* with the enhancement of technological levels, aligning with the conclusions of this study (Chishti and Sinha, 2022; Villanthenkodath and Mahalik, 2022). (4) The impact factor of ER is significantly positive. For every one-unit increase in ER, EQ increases by 0.263 units, indicating a significant promoting effect of ER on EQ. Environmental regulations in China enforce emission standards and restrictions on enterprises, compelling them to take measures to reduce pollutant emissions. This fosters enhanced clean production and technological innovation within enterprises and can also elevate public and corporate awareness of environmental protection, thereby driving improvements in *EQ*. Tang and Feng respectively focus on China and the Yangtze River Economic Belt as their study subjects, empirically analyzing the influence of environmental regulations on regional *EQ*. The results consistently demonstrate that regional *EQ* improves with the enhancement of environmental regulations, corroborating the findings of this study (Tang et al., 2020; Feng et al., 2023).

5.4 Results and discussion of the threshold regression model

5.4.1 Results

To further verify the inverted "U" relationship between Chinese *GI* and *EQ*, this paper examines the threshold variable *lnGI* under three different threshold conditions. Specifically, we investigated the cases where *lnGI* has no threshold, has one threshold, and has two thresholds. The F-statistics and *p*-values for each threshold test are presented in Table 7. The threshold variable *lnGI* only passed the single threshold test at a significance level of 1%, not passing the double and triple threshold tests. The estimated single threshold value and its 95% confidence interval for the threshold variable *lnGI* are shown in Table 8. The estimated value for the single threshold is 2.196. Therefore, *GI* has a significant impact on *EQ*, and there is a single threshold effect. The results of the threshold regression model are shown in Table 9.

TABLE 7 Threshold test (bootstrap = 10,000 10,000 10,000).

Threshold variable	Scenarios	Fstat	Prob
lnGI	Single	145.21	0.000
	Double	36.71	0.365
	Triple	22.56	0.219

TABLE 8 Threshold estimation results (level = 95).

Scenario	Threshold	Lower	Upper
Single	2.196	2.011	2.381

TABLE 9 Single threshold regression results.

Variable	Coefficient
lnPGDP	−0.113**
lnTP	0.165
lnIS	0.141***
lnTL	−0.430***
lnER	−0.330**
lnGI (*lnGI* ≤ 2.196)	0.685***
lnGI (*lnGI* > 2.196)	−0.277***
Cons	0.231***
R-squared	0.869
Prob > *F*	F = 0.000

***$p < 0.01$, ** $p < 0.05$.

5.4.2 Discussion

The results indicate that the threshold variable *lnGI* passes the statistical test at a 1% significance level, whether it is less than 2.196 or greater than 2.196. When *lnGI* is less than 2.196, the impact coefficient is 0.685, indicating a significant promoting effect of *GI* on *EQ*. With the increase of *GI*, *EQ* also improves. When *lnGI* is greater than 2.169, the impact coefficient is −0.227, indicating a significant inhibitory effect of *GI* on *EQ*. With the increase of *GI*, *EQ* decreases. The conclusion of the threshold regression model is consistent with the fixed-effects regression model, both indicating an inverted "U"-shaped impact of *GI* on *EQ*.

5.5 Regional comparative analysis

The preceding analysis examined the impact of *GI* on China's *EQ* at the aggregate sample level. However, there exist disparities among China's 30 provinces in terms of *EQ*, levels of *GI*, and geographical location. For different types of provinces, the influence of *GI* on their *EQ* may vary. Hence, this study conducts a comparative analysis of Chinese provinces from three major perspectives: *EQ* level, *GI* level, and geographical location. The present study categorizes the 30 sample provinces of China based on their geographical locations into four regions: Eastern, Central, Western, and Northeastern regions. Additionally, provinces are divided into high and low *GI* levels and further categorized into high-pollution and low-pollution provinces based on their *EQ* levels. Empirical analyses are then conducted for each category, with the respective results presented in Tables 10, 11, and 12.

Regression results for the comparison of samples based on geographical locations are shown in Table 10. *GI* exhibits significant impacts on the *EQ* of China's Eastern, Northeastern, Central, and Western regions. Specifically, there is an inverted U-shaped relationship between *GI* and *EQ* in the Eastern and Central regions. Meanwhile, there exists a certain promoting effect on the *EQ* of the Northeastern and Western regions, with the promoting effect being more pronounced in the Northeastern region. The Eastern and Central regions of China boast developed economies and possess well-established financial systems and insurance markets, laying a solid foundation for the development of *GI*. Moreover, the rapid economic growth in these regions has brought about prominent environmental issues, compelling both the government and enterprises to prioritize environmental protection and consequently increasing the demand for *GI*. The market share of *GI* has undergone stages from initial development to saturation and then to oversupply. Therefore, there exists an inverted *U*-shaped relationship between *GI* and the improvement of *EQ* in the Eastern and Central regions of China. Conversely, the Northeastern and Western regions exhibit relatively weaker economic development, resulting in slow progress in regional *GI* development, which has yet to reach saturation. Consequently, the roles of *GI*, such as economic incentives and penalties, environmental responsibility tracking, and risk sharing, are more pronounced, thereby fostering improvements in regional *EQ*. The Northeastern region, in particular, has undergone industrial transformations, facing severe pollution issues from legacy industrialization. The significant demand from the government to enhance *EQ* in this region amplifies the promoting effect of *GI*, making it more pronounced in the Northeastern region.

The regression results for the comparison of samples based on levels of *GI* are presented in Table 11. *GI* exhibits an inverted *U*-shaped relationship with the improvement of *EQ* in provinces with high levels of *GI*, while it shows a promoting effect in provinces with low levels of *GI*. In provinces with high levels of *GI*, the market share of *GI* has undergone stages from initial development to saturation and then to oversupply, resulting in an inverted *U*-shaped impact on *EQ* improvement. Conversely, in provinces with low levels of *GI*, where the market share of *GI* has not yet reached saturation, the positive effects of *GI*, including economic incentives and penalties, technological upgrades, environmental responsibility tracking, and risk sharing, are significant.

The regression results for the comparison of samples based on *EQ* levels are depicted in Table 12. *GI* exhibits only a promoting effect on the improvement of *EQ* in both high-pollution and low-pollution provinces, without displaying an inverted *U*-shaped relationship. This can be attributed to several factors. Firstly, although high-pollution provinces demonstrate a strong demand for *EQ* improvement, some provinces with lower levels of economic development hinder the rapid growth of the *GI* industry. Consequently, the impact of *GI* on *EQ* improvement remains in the promoting stage. Secondly, low-pollution provinces, benefiting from relatively better *EQ*, do not urgently require the development

TABLE 10 Compare the regression results by sample based on geographical location.

Variable	Coefficient			
	Eastern Region	Central Region	Western Region	Northeastern Region
ln GI	0.545**	0.419**	0.485***	0.645**
$lnGI^2$	−0.129***	−0.096***	/	/
lnPGDP	−0.319***	−0.115***	−0.207**	−0.212***
lnIS	−0.110**	−0.327**	−0.189***	−0.295**
lnTL	0.097***	0.177***	0.221***	0.155**
ln ER	0.221***	0.183***	0.229***	0.363***
R-squared	0.884	0.859	0.903	0.911
Prob > F	0.0000	0.0000	0.0000	0.0000

***$p < 0.01$, ** $p < 0.05$.

TABLE 11 Compare the regression results by sample based on levels of *GI*.

Variable	Coefficient	
	Provinces with high levels of GI	Provinces with low levels of GI
ln GI	0.351**	0.681**
$lnGI^2$	−0.081***	/
lnPGDP	−0.119***	−0.335***
lnIS	−0.201**	−0.130***
lnTL	0.092***	0.209***
ln ER	0.149***	0.223***
R-squared	0.917	0.893
Prob > F	0.0000	0.0000

***$p < 0.01$, ** $p < 0.05$.

TABLE 12 Compare the regression results by sample based on levels of *EQ*.

Variable	Coefficient	
	High pollution provinces	Low pollution provinces
ln GI	0.582**	0.448**
$lnGI^2$	/	/
lnPGDP	−0.311***	−0.235***
lnIS	−0.283**	−0.155**
lnTL	0.123**	0.228***
ln ER	0.255***	0.193***
R-squared	0.892	0.858
Prob > F	0.0000	0.0000

***$p < 0.01$, ** $p < 0.05$.

TABLE 13 Robustness test results.

Variable	Coefficient	
	Robustness test (1)	Robustness test (2)
	Express the explanatory variable as the income from environmental pollution liability insurance.	Calculate regional EQ using principal component analysis.
ln GI	0.367 **	0.297 **
$lnGI^2$	−0.084 ***	−0.069 ***
R−squared	0.866	0.912
Prob > F	0.000	0.000

***$p < 0.01$, ** $p < 0.05$,

of the *GI* industry. This results in sluggish regional development of the *GI* industry, maintaining its impact on *EQ* in the promoting stage.

5.6 Robustness test

Robustness tests ensure that model results remain reliable and effective when facing various potential anomalies, thereby enhancing the credibility and interpretability of the research. A review of relevant literature reveals that common methods for conducting robustness tests include: altering sample periods, substituting the dependent variable, introducing additional control variables, and changing the measurement methods of variables (Ferreira et al., 2017).

This study conducts robustness tests by changing the expression indicators of explanatory variables and the calculation methods of the dependent variable. The test results are presented in Table 13. Due to space limitations, the details of control variables are not elaborated in Table 13. A comparison between Table 6 and Table 13 reveals the following: (1) The study measures the level of *GI* development in various provinces of China using the proportion of regional environmental pollution liability insurance income to total premium income. The regional environmental pollution liability insurance income is used as the dependent variable during validation. After changing the expression indicators of explanatory variables, the coefficients of explanatory variables in Table 13 are largely consistent with those in Table 6. (2) *EQ* was initially measured using entropy methods in the previous sections, while principal component analysis is employed in this study. Despite this change in the measurement method of *EQ*, the robustness test results still indicate a quadratic relationship (inverted U-shaped) between *GI* and *EQ*. In summary, the robustness test results further confirm the strong reliability of the estimated results of the nonlinear panel regression model constructed in this study.

6 Conclusions and suggestions

6.1 Conclusions

As an innovative product integrating environmental protection and the financial sector, *GI* provides a new avenue for enhancing *EQ*. Existing research outcomes predominantly focus on the linear relationship between *GI* and *EQ* or simplistic notions of positive and negative impacts. However, this study, through the identification of an inverted U-shaped relationship, broadens the research perspective on the influence of *GI*. The unveiling of such a nonlinear relationship offers a more profound and comprehensive understanding of *GI* research, enriching the discourse on the nuanced dynamics of its impact. This paper focuses on China and empirically analyzes the impact of *GI* on *EQ*. The results indicate: (1) The fixed-effects regression model demonstrates that the impact of *GI* on China's *EQ* follows an inverted "U"-shaped pattern. (2) The results of the threshold regression model also support the inverted "U"-shaped relationship, with a threshold value of 2.196. (3) Economic level and industrial structure exert a significantly inhibitory effect on improving *EQ*, while technological level and environmental regulation have a significant promoting effect. Population size does not show a significant impact on improving *EQ*.

6.2 Policy implications

At present, the government promotes the development of *GI* through measures such as tax incentives, government procurement, and reward mechanisms, with a singular focus on maximizing the *GI* market. However, this study reveals that an excessively high level of the *GI* market exerts a suppressive effect on environmental improvement. Therefore, differentiated policies tailored to the characteristics of different stages of *GI* development are essential. In the initial stages, the government should prioritize incentivizing, guiding, and supporting the establishment of the market. Various multidimensional measures should be implemented to provide impetus and a foundation for the development of *GI* institutions, promoting their stable growth in the early market.

Firstly, the government can encourage and guide *GI* institutions to enter the market by offering economic incentives, tax benefits, special funds, and other incentivizing policies. Secondly, through regular discussions and seminars, the government can actively guide deep cooperation between *GI* institutions and the environmental protection industry, inspiring these institutions to better adapt to the needs of the environmental protection industry.

In the later stages of *GI* development, the government should focus on upgrading *GI* products, fostering collaborations, and managing market risks to ensure a more significant role for *GI* in the field of environmental protection and achieve a win-win situation between

environmental protection and the economy. **Firstly**, the government should encourage continuous improvement in the technical content and adaptability of *GI* products. This can be achieved through reward mechanisms for technological innovation, support for intellectual property protection, and the provision of favorable conditions for the research and development of *GI* products. The government can establish dedicated technology innovation bases or laboratories, providing resources and collaboration platforms for institutions to drive continuous innovation in *GI* products, environmental monitoring technologies, and assessment methods, enhancing the quality and effectiveness of *GI* products. **Secondly**, the government should actively guide *GI* institutions to collaborate and co-build with environmental organizations, research institutions, and enterprises. Regular discussions and seminars can be employed to strengthen the exchange of professional knowledge. Environmental organizations and research institutions often possess the latest environmental technologies and scientific research results, while enterprises understand actual operational conditions. By leveraging resources from various parties, a forward-looking and innovative project can be created, constructing a closed-loop industry chain from environmental technology research and development to practical application in enterprises, and further to the design and promotion of *GI*. This comprehensive approach ensures all-encompassing environmental management from the source to the end. **Finally**, the government needs to strengthen market risk management for *GI* to ensure its healthy operation. This involves comprehensive monitoring of market monopolies, unfair competition, and the financial conditions of *GI* institutions. The government can enact and implement relevant regulations, establish regulatory bodies, or enhance the functions of existing regulatory bodies to effectively address potential risks and uncertainties. This is crucial for maintaining the overall safety of the *GI* market.

On the other hand, this study reveals significant inhibitory effects of economic level and industrial structure on the improvement of *EQ* in China, while technological level and environmental regulations demonstrate significant promoting effects. Consequently, we propose policy recommendations to promote the enhancement of *EQ* in China from four dimensions: economic level, industrial structure, technological level, and environmental regulations. (1) Economic Development: Establishing a green product certification system to certify products that meet environmental standards and assign them corresponding green labels would help consumers identify and choose green products, enhancing their confidence in purchasing them. Conducting extensive environmental propaganda and education campaigns through various channels such as media, the internet, and communities would raise awareness among residents about the importance and benefits of green consumption, thereby increasing public understanding and consciousness of green consumption. (2) Industrial Development: The government should formulate and implement targeted industrial policies to clarify development directions and key areas. Measures such as tax incentives, fiscal subsidies, and land policies should be adopted to encourage and support the upgrading of industrial structure. Encouraging the construction of green industrial clusters and parks and increasing investment in infrastructure construction in green industrial parks would facilitate the entry of upstream and downstream enterprises in the industrial chain, thereby forming a complete green industrial chain and value chain. (3) Technological Advancement: The government should establish a green technology innovation fund to increase investment in scientific and technological innovation, supporting R&D and innovation in green industries to enhance technological levels and product quality. Additionally, establishing and supporting green technology incubation platforms to provide services such as technology transfer, professional consultation, and market promotion would assist research institutions and enterprises in translating technological achievements into practical productivity. (4) Environmental Regulations: Enhancing the legal system for environmental laws and regulations and enacting stricter environmental protection laws and regulations are essential to ensure the legal guarantees for the development of green industries and create a fair competitive market environment. Establishing an environmental information disclosure system to promptly release environmental monitoring data and emission information of green industry enterprises to the public would increase public attention and participation in environmental issues.

6.3 Limitations

This study finds that the impact of *GI* on China's *EQ* follows an inverted "U" shape. The control variables in the econometric model constructed in this study are determined based on existing research findings. Control variables were not directly determined without analyzing the factors influencing *EQ*. Additionally, our team's research reveals that the impact of *GI* on *EQ* varies across countries with different *EQ* levels. Particularly for developed countries, *GI*'s impact on *EQ* may exhibit a dual-threshold effect. That is, *GI* might initially have a promoting effect on *EQ*, then transition to a suppressive effect, before ultimately reverting to a promoting effect.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://www.stats.gov.cn/sj/ndsj/.

Author contributions

XY: Conceptualization, Methodology, Writing–original draft. JW: Data curation, Formal Analysis, Methodology, Writing–review and editing. ZL: Investigation, Software, Validation, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The role of financial inclusion, urbanization, and energy efficiency on environmental performance in belt and roads initiative (BRI) economies

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The primary objective of the study is to determine how environmental performance is affected by several factors, including trade freedom, industrial production, urbanization, financial inclusion, and energy efficiency. This research provides a novel perspective on the environmental performance of Belt and Roads Initiatives (BRI) member states by employing panel data from 1991 to 2021. It contributes to our understanding of the role of several factors in improving environmental performance. Panel data analysis also incorporates the CD, CIPS, FMOLS, DOLS, and PMG-ARDL tests. This research possesses substantial theoretical ramifications, as it might enable the expansion and refinement of current economic and environmental theories. As per the findings of this research, each factor significantly affects environmental performance (ecological foot-point). This contributes to short-term environmental issues by conserving resources and lowering emissions, creating the framework for long-term environmentally friendly procedures and innovation. Strong environmental policies that may cause effective environmental performance in Belt and Roads Initiatives (BRI) countries.

KEYWORDS

trade freedom, industrial production, urbanization, financial inclusion, energy efficiency, environmental performance, PMG-ARDL, belt and roads initiatives (BRI) countries

1 Introduction

National environmental-socioeconomic growth can only be governed effectively with access to enough financial resources (Baek et al., 2009; Alam et al., 2012). Green energy that is affordable and beneficial to the environment can be made possible through the spread of inclusive financing (Tayebi et al., 2016; Wardhani and Dugis, 2020). The World Bank Consultation Assist Group People in Need defines "inclusive finance" as the responsible and long-term provision of various financial goods and services, such as loans and insurance, to households and the business sector. To provide "affordable, clean energy" to all people is one of the Sustainable Development Goals set by the UN, as reported by the World Bank (Nwafor, 2014). More widespread access to financial services has been recognized as a key factor in enabling sustainability by making it possible for firms and families to invest in environmentally friendly technology and make purchases of energy-efficient goods.

Therefore, promoting financial inclusion is crucial for sustainable development since it provides the path for technologically advanced, energy-efficient products (Wang, 2023).

Meanwhile, as the economy and technology improved, so did energy needs. Energy consumption is vital to economic growth but has serious negative environmental effects (Chaabouni and Saidi, 2017; Li et al., 2020a). Global agreements, including Kyoto in 1997 and the Climate Agreement of Paris in 2015, seek to slow environmental damage based on rising emissions of greenhouse gases (Q. Wang, Wang, et al., 2024b). These agreements seek, in part, to boost energy efficiency, defined as "the ratio of energy input to economic output (Chenran et al., 2019). Businesses can reduce energy use while maintaining productivity and growth (G. Li et al., 2020b). It also indicates progress in low-carbon technologies, paving the way for studying renewable energy (Cai et al., 2018). Retooling domestic industrial sectors with renewable and energy-efficient technologies is a wise investment for countries. (Baek, 2016).

The world's nations are running to find a way to cut the release of carbon dioxide. The most important thing we can do to stop global warming is to perfect renewable energy technologies. Therefore, deciding on a renewable energy path is crucial to laying the groundwork for a low-carbon economic system. However, such an adjustment is out of the question (Rehman et al., 2021). The ecological footprint was chosen as the environmental performance indicator for the following reasons: The ecological evaluation at the heart of sustainable development is the ecological footprint, which measures humankind's impact on the environment and the resilience of the planet's bio-system. It is an essential indicator for measuring SDG progress (Khan and Hou, 2021). Second, the ability to absorb waste is crucial to ecological sustainability. Businesses make use of everything from minerals and wood to soil and water. In contrast to pollutants, which do not consider these things, the ecological footprint seems more complete (Li R. et al., 2023). To illustrate people's environmental impact, we may look at our "ecological footprint" (Danish et al., 2020).

Put another way, compared to individual indicators like CO2 carbon footprints, greenhouse gas emissions, and other contaminants, it provides a more comprehensive picture of environmental degradation and financial viability (Wang, 2024). Industrial production has been essential to developing sophisticated economies ever since the commencement of the Industrial era. Additional emissions of greenhouse gases frequently hinder developing and emerging nations from achieving their ambitious economic goals. To build economies and get people out of poverty, these countries need to increase industrial production through manufacturing, which uses much energy. Production often results in the release of carbon dioxide (Ge, 2023). A key contributor to carbon emissions is the ongoing expansion of economic activity, which boosts energy needs (H. Wang et al., 2022). The novelty of this research explores the relationship between trade openness, industrial production, urbanization, energy efficiency, financial inclusion, and environmental performance. It emphasizes the complexity of these relationships and uses sector-based analysis, geographical dimensions, novel technologies, and social justice ethics to develop innovative ways to manage and regulate the environment.

In addition, expanding industrial production is indistinguishably related to ecological impacts because of continued resource extraction. The ecological footprints of industrialized nations are greater than those of less developed ones (Wang et al., 2024a). Compared to the United States and China, the two largest polluters over the past two decades, nations like Malaysia, Cambodia, Indonesia, and Korea have ecological footprints far below one billion global hectares (gha). This difference strengthens the developing world's well-known stance on shared but separate obligations (Chandio et al., 2023). Therefore, it is essential to understand the energy problem facing the Roads and Belt Initiative (BRI) by explaining the connection between industrial productivity and environmental performance. For the BRI member states, it is essential to permit industrial production to become a tool in developing the national economy. The economic, energy, and environmental perspectives highlight three key ideas: financial industry development, economic enablers, and the effects of energy efficiency on ecological productivity (Li T. et al., 2023). The financial sector provides many options to create innovative tools that can help deal with environmental threats. Recently, renewable energy solutions, in conjunction with environmentally friendly and advanced energy, are two concepts that can be depicted as two sides of a coin. Such aspects of economic management, as mentioned above, are the critical environmental management indicators of trade freedom, industrial productivity, and urbanization. It protects the environment and provides energy efficiency and financial inclusion (Xu et al., 2023). Renewable electricity industries in developing countries expand. Therefore, industries in countries where the financial market is growing professionally tend to develop even faster than those where the debt market is underdeveloped and financial institutions are unstable (Ahsan et al., 2020; Ali et al., 2021).

This research examines how the environment is affected by financial inclusion (FI), energy efficiency (EE), and economic factors like trade freedom, industrial production, and urbanization. This research proposes new conclusions and suggestions about how financial inclusion, energy efficiency, and economic factors affect environmental performance. There are three primary reasons why this study's contribution matters: (1) the ecological footprint is used as an all-encompassing environmental performance metric in this study. The study used the PMG-ARDL model to identify the short and long-run association along with the effect of the variables on the environmental performance. (2) Renewable energy consumption is a proxy for energy efficiency, a novel metric not previously utilized in research. Despite East Asia and the Pacific's more significant population, higher energy consumption, and higher emissions, (3) the Belt and Road Initiatives should be recognized in the scientific literature.

1.1 Research objectives

The objectives of this study are as follows:

- To assess the influence of economic factors on environmental performance.
- To determine the influence of financial inclusion on environmental performance.

- To evaluate the influence of energy efficiency on environmental performance.

2 Review of literature

2.1 Theoretical foundation

2.1.1 Ecological modernization theory

According to the ecological modernization theory, technological upgrading and restructuring the economy are ways of helping society achieve sustainability, which is the responsibility of sociology and political science. (Ahsan et al., 2020). It recognizes that industrialization and economic development are among the activities that have historically resulted in environmental disruptions but are more optimistic about the future (Xu et al., 2023). The theory implies that through green technologies and eco-friendly practices, we can build an economy that is sustainable and close to natural conditions. Economic growth in an environmentally responsible way can become a self-reinforcing force. Hence, markets and government regulation can simultaneously drive environmental improvements; firms can find economic opportunities in green innovation, and the public can demand higher environmental standards via their choices and values. This theory has contributed a lot to environmental policy improvements and the utilization of modernization processes to minimize environmental pollution (John and Hana, 2021).

2.1.2 Social Capital Theory

The Social Capital Theory that has emerged in sociology focuses on the importance of social relations, networks, and interactions, which can contribute to achieving personal objectives and common goals. One can always rely on the fact that, regardless of the adverse phases of life, mutual trust and personal connections will always provide wellbeing to the individual and community. Social capital describes the embedded resources of social networks, for example, information, support, combination, and accessibility opportunities (Hu et al., 2021). It can be categorized into two main types: at the same time, it is the combination of social capital that relates to the strength of connections between local communities and social capital that connects different communities on an enormous scale. A social setting with solid social network members may produce positive results for the people involved, including increased educational prospects or employment openings and general harmony in the community (Hussain et al., 2021).

2.2 Empirical evidence

According to Chaudhry et al. (2022), this study was based on the "Dynamic Common Correlated Effects" method employed to identify the influence of financial integration on environmental degradation across the Organization of Islamic Cooperation members from 2004 to 2018. The findings showed that CO2 emissions, CH4 emissions, and degradations are the only variables significantly related to high-income OIC member economies. In contrast, nitrogen dioxide emissions and ecological footprint appear to be independent of variations in income levels. Low-income countries with the shapes of low-income countries and all OIC nations that reversed the UV-shaped environmental Kuznets curve were also deforested. As the report indicates, nature capacity should be the highest concern and priority in government management for nature protection, sustainable forest use, and the necessary finance services.

Based on the researchers Zhao and Yang's (2020) findings, the relationship between financial inclusion and CO2 emissions at the provincial level in China is claimed to exist. The study suggested that with financial inclusion increasing by 10%, national emissions could drop by 4%–5%. It has only three exceptions: Zhejiang, Fujian, and Xinjiang. To reduce CO2 emissions, the report suggests that China's province concentrate on developing its financial sector and gives examples for local governments. Usman et al. (2021) explored a correlation between economic development, renewable energy usage, and GDP increases in 15 countries that ranked high in carbon emissions as preferred between 1990 and 2017. The findings demonstrate that trade freedom, renewable energy sources, and financial development can mitigate climate change. At the same time, economic growth and the consumption of fossil fuels are, for the most part, the most significant contributing factors. It was established during the study that a two-way influence exists between the features. The ecological footprint, which is negatively associated with trade freedom and renewable energy, can be used as an indicator while emphasizing the import of trade and energy balance.

According to Koomson and Danquah (2021), the study used data from lifestyle surveys to discover that financial inclusion is connected to energy poverty in Ghana. Increased financial inclusion can minimize energy poverty, translating to the most predictable outcomes in rural areas and families headed by men. At this juncture, staff members gain the most from the higher financial accessibility. The most held possible avenues are household net income and type of family.

According to Id et al. (2023), the research applied econometric tools to evaluate the impact of foreign direct investment (FDI) on technical innovation in BRICS countries from 2000 to 2020. This research indicates that inward foreign direct investments, an increase in trade openness, economic growth, and commitment of more money to research all lead to an increase in innovations. Rauf et al. (2023) investigated how foreign direct investment, energy use, and technical innovations affected BRICS countries' economic growth and quality of the environment in 1990 and 2018. This suggests that FDI positively impacts growth but impairs sustainability, while innovation technology improves sustainability.

Xu et al. (2023) studied the effects of energy conservation campaigns and adopting alternative energy sources on the level of carbon dioxide emissions from the MENA region's electrical industry. The considerable non-renewable energy intensity is alarming. On the other hand, the intensity of renewable energy is below the breakeven point. Examples of renewable and non-renewable energy sources could be switched into capital energy. The MENA region's poor energy efficiency and track record of climate mitigation show that clean, cheap energy and climate change execution will only be possible through pure economic growth by the end of 2030. The study suggests that improvements or setbacks in energy efficiency may result from government subsidies.

As the researchers of Lin and Abudu (2020) indicate, energy efficiency, renewable energy, and the extent of industrial composition will still, over time, influence the level of greenhouse gas emissions. There is substantial proof that a decrease in CO2 emissions in the long term is attained through energy efficiency. Moreover, CO2 emissions are reduced when renewable energy is substituted for non-renewable energy. The study further shows that real income and industrialization are the two variables that led to the increase in the level of C02. Dong et al. (2018) demonstrated that the Environmental Kuznets Curve (EKC) for China's greenhouse gas pollution uses a new paradigm. It assesses the dynamic impact of fossil fuel's replacement with renewable energy sources on the emission of CO2. Study data show the positive effect of clean energy sources on CO2 emissions. The results confirm the existence of the EKC for CO2 emissions in China. Gradual emission reduction is only possible with natural gas. It is presently eclipsed as part of the renewable energy mix. Policies and suggestions for cutting carbon emissions throughout the development of these sectors are strongly supported. Abbas et al. (2022) examined the impact of renewable energy growth, market regulation, and environmental innovation on CO2 emissions from BRICS nations in 1990–2020. The findings suggest a long-term correlation in which market regulation acts as a moderator. Initiatives such as market-based methods and taxation linked to the environment will also be among our strategies.

Magazzino (2015) states that a time series analysis investigated the relationship between GDP and energy consumption in Italy between 1970 and 2009. The study shows that both series are not stationary and have cointegration. Energy consumption and GDP share a causative relationship over a short period, and then the relationship becomes bidirectional in the long run. Dou et al. (2021) stated that the relationship between trade liberalization and carbon emissions in the China-Japan-South Korea area in 1970–2019 was examined. The agreement can lessen the promotion effect of trade freedom, which favorably impacts the greenhouse effect. When countries import more, their carbon emissions rise, and when they export, their emissions drop dramatically. Freer trade indirectly affects carbon emissions through changes in scale, technology, and the economy's underlying structure. Policy recommendations for reducing the greenhouse effect and increasing high-quality Trade freedom are included in the report.

Wen et al. (2021) demonstrated the association between environmental quality and green innovation in South Asian countries. The study employs panel co-integration tests using FMOLS and DOLS to analyze long-run correlations using panel data from 1990 to 2014. The findings demonstrate how green innovation greatly enhances environmental quality and provides South Asia with policy alternatives for environmental sustainability.

Magazzino (2016) examined six GCC nations' (Gulf Cooperation Council) real GDP, CO2 emissions, and energy usage during 1960–2013. Results demonstrate unit roots, with a definite long-run link only identified in Oman. Granger causality analysis reveals that energy consumption is the primary factor in Kuwait, Oman, and Qatar's real GDP. The Kingdom of Saudi Arabia has yet to settle on a committed partnership. The research contradicts the common belief that energy does not influence economic expansion, implying that comprehensive energy policy may need to be revised.

Sengupta et al. (2019) demonstrated the correlation between economic and environmental performance in manufacturing sectors in India and China is centered on output and export. Because of its importance to the economy and exports, manufacturing often experiences fast export-led expansion that raises environmental problems. Using unit root tests and Johansen co-integration tests, data from the World Bank are analyzed starting in 1970 and continuing through 2016. The findings demonstrate a close correlation between China's manufacturing output and CO2 emissions, with China's impact being more significant than India's. China's enormous carbon dioxide emissions are exacerbated by the country's extensive export of produced products.



FIGURE 1
Conceptual framework.

According to Hardiyansah et al. (2021), disclosure of carbon emissions and moderating factors as they relate to company value. It uses the 82 Indonesian firms awarded ISRAs between 2014 and 2018 and traded on the Indonesia Stock Exchange. The findings demonstrate that investors consider carbon emission disclosure as part of evaluating a company's sustainability and that this disclosure favors industrial production. Environmental performance and industrial type also influence the connection since organizations with ISO 14001 certificates try to ensure environmental sustainability. According to the study (Ferraris, 2022), the leather industry emphasizes industrial production vs. environmental performance (EP) and the mediating function of individual green values (IGV). The study used a resource-based theoretical framework to conclude that industrial production has a net positive effect on EP and makes an immense contribution to IGV development, affecting EP. However, the study found that government measures should dampen the link between industrial production and IGV.

3 Methodology

3.1 Conceptual framework

The conceptual framework was developed after thoroughly reviewing the relevant academic literature. The current study investigates the relationship between environmental performances (ecological foot-point) as the dependent and independent variables, including trade freedom, industrial production, urbanization,

TABLE 1 Description of variables (Source: World economic indicators).

Variables	Code	Measurement
Independent Variables		
Trade Freedom	TF	Imports of goods and services (% of GDP)
Industrial Production	IP	Value added (constant 2015 US dollars), industry (incl. construction)
Urbanization	UR	Urban population growth (annual %)
Financial Inclusion	FI	FI is an index that measures the accessibility, depth, and efficiency of financial services
Energy Efficiency	EE	Renewable Energy Consumption % of total final energy consumption
Dependent Variable		
Ecological Foot-point	EF	Total Global hectare

financial inclusion (FI), and energy efficiency (EE). The entire framework of the investigations is depicted in Figure 1.

3.2 Research hypothesis

H1a. TF has a significant long-run influence on the EP (Ecological Foot-point).

H1b. TF has a significant short-run influence on the EP (Ecological Foot-point).

H2a. IP has a significant long-run influence on the EP (Ecological Foot-point).

H2b. IP has a significant short-run influence on the EP (Ecological Foot-point).

H3a. UR has a significant long-run influence on the EP (Ecological Foot-point).

H3b. UR has a significant short-run influence on the EP (Ecological Foot-point).

H4a. FI has a significant long-run influence on the EP (Ecological Foot-point).

H4b. FI has a significant short-run influence on the EP (Ecological Foot-point).

H5a. EE has a significant long-run influence on the EP (Ecological Foot-point).

H5b. EE has a significant short-run influence on the EP (Ecological Foot-point).

3.3 Data

Table 1 describes the factors used in the investigation. Trade freedom is defined as imports of goods and services (% of GDP); industrial production as a Value added (constant 2015 US dollars); urbanization is measured by population growth (annual %); financial inclusion is an index that measures the accessibility, depth, and efficiency of financial services; energy efficiency is measured by renewable energy consumption, which is % of total final energy consumption. Ecological footprint is measured in a total global hectare. The present study selected fifteen BRI countries for their initiative regarding the environment and strategic location in the continent, which possess unique geographical importance and advantages. This study is based on World Bank Indicator (WDI) data between 1991 and 2021. We converted all of them to logarithmic form to adjust for heteroscedasticity and lower the coefficients of the research variables.

3.4 Cross-sectional dependence

Pesaran (2007) states that panel data constantly endure from cross-sectional dependence (CSD). According to the literature on CSD, conventional panel models are obsolete. Inadequate reporting of common-sequence dependence (CSD) of unobserved common factors reduces the accuracy of panel data, leading to inaccurate estimations (Phillips and Sul, 2003; Pesaran, 2004).

3.5 Panel unit root test

The panel unit root test method should be used if CSD is detected. This study employs the CSD augmented Im, Pesaran, and Shin test (CIPS) and (Pesaran, 2007)' test to investigate the stationarity of the variables. The CIPS tests enhance the first-generation panel data unit root tests, which do not include CSD. (Raza and Shah, 2017).

3.6 Panel cointegration test

The next step is to assess the long-term relationship through panel cointegration techniques. When I (1) appear in a series, studying the equilibrium state over numerous iterations is worthwhile. We use three distinct panel cointegration tests to determine whether or not the variables in the study are

independent: the Pedroni test (Pesaran, 2007), the Kao test (Kao, 1999), and the Westerlund test (Westerlund, 2007). The effects of CSD and heterogeneity can be reduced by using the Westerlund panel cointegration test.

3.7 Model specification

This study uses a panel of FMOLS models to make long-term predictions. According to Chan (2005), one of the best techniques to analyze panel econometric heterogeneity is with FMOLS. To accommodate variability, this strategy reweights the data using the long-run covariance of cross-section estimates. We use the Group-FMOLS technique to anticipate the parameters' intermediate and long-term correlations. The PMG-ARDL model (Ashraf et al., 2023) is used to analyze environmental performance concerning variables like trade freedom, industrial production, urbanization, and financial inclusion. Despite significant differences in short-run dynamics between countries, the pooled mean group assures that long-run coefficients are comparable. Al-Mulla et al. (2013) found that coefficients can indicate both short-term and long-term heterogeneity when the MG closely monitors the PMG estimate. If the findings of the previous methodologies do not show cointegration, the Panel Autoregressive Distributed Lag (ARDL) analysis is used. If the underlying regressors show me (0), me (1), or a combination of the two, the macro panel data technique is preferred (Pesaran and Shin, 1998), and the period exceeds 20 years. The dataset could have been more conducive to using the GMM estimator. To assess the relationship between government debt and GDP growth, we consult the extensive literature on dynamic panel data and use a variety of estimators, including Mean Group (MG), Pooled Mean Group (PMG), and Dynamic Two-Way Fixed Effect (DFE) (Pesaran and Smith, 1995; Pesaran et al., 1999). This study used the Pooled Mean Group-Autoregressive Distributed Lag (PMG-ARDL) model, which was proposed by Pesaran et al. (2007). It is about merging and averaging the coefficient across the cross-sectional units. According to existing research, this strategy outperforms prior single co-integration procedures, such as those used by Engle and Granger (1986) and Johansen and Juselius (1990), resulting in a superior econometric model. Unlike Engle and Granger (1986), this model does not suffer from endogeneity or the inability to test hypotheses on estimated coefficients across time. This research used the following empirical model in this case:

$$
\begin{aligned}
LnEF_{it=} \propto_1 &+ \sum_{\vartheta=1}^{n} \propto_{1\propto} \Delta\, LnEF_{it-\vartheta} + \sum_{i=0}^{n} \propto_{2\propto} \Delta\, LnTF_{it-\vartheta} \\
&+ \sum_{i=0}^{n} \propto_{3\propto} \Delta\, LnIP_{it-\vartheta} + \sum_{i=0}^{n} \propto_{4\propto} \Delta\, LnUR_{it-\vartheta} \\
&+ \sum_{i=0}^{n} \propto_{5\propto} \Delta\, LnFI_{it-\vartheta} + \sum_{i=0}^{n} \propto_{6\propto} \Delta\, LnEE_{it-\vartheta} \\
&+ \beta_1\, Ln(EF_{t-1}) + \beta_2\, Ln(TF_{t-1}) + \beta_3\, Ln(IP_{t-1}) \\
&+ \beta_4\, Ln(UR_{t-1}) + \beta_5\, Ln(FI_{t-1}) + \beta_6\, Ln(EE_{t-1}) + \epsilon_{2it}
\end{aligned}
$$

Table 1 provides information about the variable inputs.

4 Results

4.1 Descriptive statistics

Table 2 displays the descriptive statistical data for the variables. The average values for ecological footprint, energy efficiency, urbanization, financial inclusion, industrial production, trade freedom, and environmental performance are shown below. 7.743, 2.925, −1.169, 17.186, and 3.808, respectively. The minimum and highest values are 12.810, 22.362, 5.339, 29.383, 1.672, −0.159, and 4.512, respectively, with a range of −1.109 to −4.405 and −3.553 values. The standard deviation numbers are as follows: 1.462, 0.2255, 0.560, 2.749, 0.683, and 0.710. After using skewness, kurtosis, and Jarque-Bera tests to guarantee data normality, the results of this investigation were found to be expected.

4.2 Correlation matrix analysis

Environmental performance (ecological foot-point), energy efficiency, urbanization, financial inclusion, industrial production, trade freedom, and a correlation matrix demonstrate the relationship between these and other factors. Table 3 indicates that all factors had a positive and negative connection with ecological foot-point or environmental performance.

4.3 Cross section dependency test and unit root test

Table 4 shows the results of the cross-sectional dependencies (CD) test using the approach (Pesaran, 2004). This section discusses the empirical part of the study. The findings imply the presence of transnational dependencies, which contradicts the notion of cross-sectional independence. The findings show that events in one country might have a knock-on effect on the other countries under consideration. Based on the CD test results, the next step is assessing the degree of series stationarity. Remember that the research process is constructed so each stage runs independently to avoid inconsistencies. The CIPS employs a dependable method for establishing international correlations: the Second-generation panel unit root test. The results of testing the CIPS panel for unit roots are shown in Table 4. We used a CIPS-style unit-root test to check the stationarity of the three variables. However, when the 1% difference and trend thresholds are met, all variables approach stationary. (1) Integrating to the first order does not demonstrate that the variables are stationary. There is one unit root for the variable. So, we can reject Hypothesis 0.

4.4 FMOLS and DOLS test

Table 5 shows the anticipated values of the FMOLS and DOLS models. The coefficients of these models can be used to calculate the long-term implications. The FMOLS model for TF, IP, UR, and FI is positive, whereas the DOLS model for EF is negative; both models are statistically significant at 1% and 5%, respectively. Similarly, at

TABLE 2 Descriptive statistics.

	Ln (EF)	Ln (TF)	Ln (IP)	Ln (UR)	Ln (FI)	Ln (EE)
Mean	17.186	3.808	23.791	0.743	−1.169	2.925
Median	17.342	3.843	24.397	0.810	−1.059	3.404
Maximum	22.362	5.339	29.383	1.672	−0.159	4.512
Minimum	12.810	2.364	17.442	−4.405	−3.553	−1.109
Std. Dev	2.254	0.560	2.749	0.683	0.710	1.462
Skewness	0.072	0.350	−0.640	−2.732	−0.622	−1.408
Kurtosis	2.610	3.124	2.895	17.527	2.538	3.820
Jarque-Bera	3.059	8.965	2.292	4.564	3.283	4.649
Probability	0.217	0.011	0.216	0.189	0.106	0.209

Notes: TF, trade freedom; IP, industrial production; UR, urbanization; FI, financial inclusion; EE, energy efficiency, and EF , Ecological foot-point.

TABLE 3 Correlation analysis.

Correlation	Ln (EF)	Ln (TF)	Ln (IP)	Ln (UR)	Ln (FI)	Ln (EE)
Ln (EF)	1					
Ln (TF)	−0.185	1				
Ln (IP)	0.805	−0.203	1			
Ln (UR)	0.320	0.124	0.029	1		
Ln (FI)	0.401	0.060	0.706	−0.140	1	
Ln (EE)	−0.039	−0.394	−0.404	0.182	−0.706	1

Notes: TF, trade freedom; IP, industrial production; UR, urbanization; FI, financial inclusion; EE, energy efficiency, and EF , Ecological foot-point.

TABLE 4 Results of CD and CIPS unit root test.

	Ln (TF)	Ln (IP)	Ln (UR)	Ln (FI)	Ln (EE)
CD	10.982	12.619	10.861	6.871	5.651
CIPS (at level)	0.8861	0.2718	0.9985	0.8854	0.7141
	n0	n0	*	***	n0
CIPS (at 1st difference)	0.101	0.0001	0.0245	0.0670	0.0002
	0.0000***	0.0035***	0.0000***	0.0000***	0.0002***

Notes: TF, trade freedom; IP, industrial production; UR, urbanization; FI, financial inclusion; EE, energy efficiency, and EF , Ecological foot-point.

1% and 5%, the TF, IP, UR, FI, and EF models of the FMOLS and DOLS are statistically significant. FMOLS and DOLS validate the relevance and long-term estimation sign of the PMG-ARDL model.

4.5 PMG-ARDL test

4.5.1 Short-run impact

Table 6 displays the outcome in the short term: The results (coefficient = 0.552, t-value = 10.180, and *p*-value = 0.000) show that trade freedom has a substantial short-term effect on environmental performance (ecological foot-point) at the 5% level of significance; thus, the (H: 1b) hypothesis has been accepted at the 1% level. This study's findings are consistent with previous research (Ferraris, 2022). The (H: 2b) hypothesis was accepted at the 1% significance level because industrial output has a significant short-term impact on environmental performance (ecological foot-point). The findings support previous investigations' findings (Ali et al., 2019). The first hypothesis (H: 3b) was accepted at the 1% level of significance because urbanization has a strong short-term impact on environmental performance (ecological foot-point) (coefficient = 0.808, t-value = 30.031, *p*-value = 0.000). This study's findings are consistent with previous investigations (Mensah et al., 2019). The (H: 4b) hypothesis was accepted at a 1% level of significance because of the positive short-term effects of financial inclusion on environmental performance (ecological foot-

TABLE 5 FMLOS and DOLS test.

Test	FMOLS				DOLS			
Variable	Coefficient	Std. Error	t-Stat	Prob	Coefficient	Std. Error	t-Stat	Prob
Ln (TF)	0.105	0.054	1.934	0.054	0.479	0.148	3.248	0.001
Ln (IP)	0.635	0.009	68.002	0.000	0.580	0.024	23.714	0.000
Ln (UR)	0.946	0.139	6.824	0.000	0.411	0.116	3.540	0.001
Ln (FI)	0.512	0.117	4.393	0.000	0.620	0.194	3.195	0.002
Ln (EE)	0.537	0.045	11.873	0.000	0.557	0.090	6.193	0.000

Notes: TF, trade freedom; IP, industrial production; UR, urbanization; FI, financial inclusion; EE, Energy Efficiency and EF , Ecological foot-point.

TABLE 6 Short-run impact.

Variable	Coefficient	Std. Error	t-Statistic	Prob	Remarks
Ln (TF)	0.552	0.054	10.180	0.000***	Significant
Ln (IP)	−6.267	0.962	−6.512	0.000***	Significant
Ln (UR)	0.808	0.027	30.031	0.000***	Significant
Ln (FI)	0.530	0.107	4.943	0.000***	Significant
Ln (EE)	0.683	0.075	9.091	0.000***	Significant
ECT (−1)	−0.264	0.067	−3.922	0.001***	Significant

Notes: TF, trade freedom; IP, industrial production; UR, urbanization; FI, financial inclusion; EE, energy efficiency, and EF, Ecological foot-point. The ***, **, and * signs indicate the significance level of 1%, 5%, and 10%, respectively.

point) (coefficient = 0.530, t = 4.943, and *p*-value = 0.000). Previous research has found the same results (Li R. et al., 2023). The findings (coefficient = 0.683, t-value = 9.091, and *p*-value = 0.000) indicate that the (H: 5b) hypothesis was accepted at the 1% level of significance and that energy efficiency has a significant short-run impact on environmental performance (ecological foot-point). The findings of this investigation are consistent with those of earlier studies (Albulescu et al., 2020). Therefore, the present study was employed to examine the short run model with the lag of ECT. The coefficient of ECT is −0.264, which indicates the speed of adjustment toward equilibrium. Here, the speed is 0.264 percent per unit.

4.5.2 Long-run impact

Table 7 displays the long-term outcomes: Based on the findings (coefficient = 0.521, t-value = 12.151, and *p*-value = 0.000) at the 5% significance level, we accept the (H: 1a) hypothesis at the 1% level of significance, which indicates that trade freedom has a significant short-run impact on environmental performance (ecological foot-point). This one was discovered in line with earlier investigations (Le et al., 2020). According to the findings (coefficient = −0.206, t-value = −2.077, and *p*-value = 0.038), industrial production significantly impacts environmental performance (ecological footing). As a result, the initial hypothesis (H: 2a) was accepted with a 1% significance level. Previous research has produced similar findings (Chaudhry et al., 2022). At a 1% level of significance, the (H: 3a) hypothesis was accepted because it showed that urbanization has a significant long-term effect on the environment (ecological foot-point) (coefficient = 0.837, t-value = 39.356, and *p*-value = 0.000). Previous research has produced similar findings (Zhao and Yang, 2020). At the 1% level of significance, the first hypothesis (H: 4a) was accepted because the long-term effects of financial inclusion on environmental performance (ecological foot-point) are statistically significant (coefficient = 0.524, t = 6.245, and *p*-value = 0.000). This study's findings are consistent with previous research (Usman et al., 2021). The findings (coefficient = 0.949, t-value = 15.984, and *p*-value = 0.000) show that energy efficiency significantly impacts environmental performance (ecological footnote). Shows that, at the 1% significance level, the initial hypothesis (H: 5a) was accepted. Other research has found similar results (Koomson and Danquah, 2021).

4.6 Dumitrescu hurlin panel causality tests

This study also investigates the impact of trade freedom, industrial output, urbanization, financial inclusion, and energy efficiency on the environmental performance (from an ecological standpoint) of Belt and Road Initiative (BRI) countries. Table 8 presents the results of the causality test. The results demonstrated a direct relationship between IP*TF and EP. Countries participating in the Belt and Roads Initiative (BRI) have their EF forecasted accurately using IP*TF. We also discovered evidence of a unidirectional causal relationship between TF and EF, implying that changes in TF levels will affect EF levels.

Furthermore, we discovered that IP predicts EF in countries participating in the Belt and Roads Initiative (BRI), indicating that the relationship is causal but only in one direction. We discovered that UR and EF are only causally connected in one way, implying

TABLE 7 Long-run impact.

Variable	Coefficient	Std. Error	t-Statistic	Prob	Remarks
Ln (TF)	0.521	0.043	12.151	0.000***	Significant
Ln (IP)	−0.206	0.099	−2.077	0.038**	Significant
Ln (UR)	0.837	0.021	39.356	0.000***	Significant
Ln (FI)	0.530	0.085	6.245	0.000***	Significant
Ln (EE)	0.949	0.059	15.984	0.000***	Significant

Notes: TF, trade freedom; IP, industrial production; UR, urbanization; FI, financial inclusion; EE, energy efficiency, and EF, Ecological foot-point. The ***, **, and * signs indicate the significance level of 1%, 5%, and 10%, respectively.

TABLE 8 Dumitrescu hurlin panel causality test.

Path of causality	W-Stat	Zbar-Stat	Prob
Ln (IP)*Ln (TF) → Ln (EF)	1.772	1.647	0.099
Ln (EF)→Ln (IP)*Ln (TF)	2.207	2.607	0.231
Ln (TF) → Ln (EF)	1.877	1.899	0.057
Ln (EF) → Ln (TF)	0.533	0.872	0.561
Ln (IP) → Ln (EF)	4.854	8.968	0.000
Ln (EF) →Ln (IP)	1.819	1.224	0.216
Ln (UR) →Ln (EF)	2.806	3.999	0.000
Ln (EF)→ Ln (UR)	1.977	0.379	0.324
Ln (FI) →Ln (EF)	3.285	2.923	0.001
Ln (EF) →Ln (FI)	1.435	1.303	0.538
Ln (EE) →Ln (EF)	2.848	2.947	0.032
Ln (EF) →Ln (EE)	0.722	0.486	0.486

Notes: TF, trade freedom; IP, industrial production; UR, urbanization; FI, financial inclusion; EE, energy efficiency, and EF, Ecological foot-point. The ***, **, and * signs indicate the significance level of 1%, 5%, and 10%, respectively.

that changes to UR will have a considerable impact on EF. Changes in FI will affect EF, as we discovered a unidirectional causal relationship between the two variables. Finally, changes to EE will affect EF because there is evidence of a one-way causal relationship between the two.

5 Discussion and conclusion

5.1 Discussion

The FMOLS and DOLS models for trade freedom, industrial production, urbanization, financial inclusion, and energy efficiency have a statistically significant coefficient of 1%. FMOLS and DOLS verify the PMG-ARDL model's long-term sign and significance estimation. The results show the short-run and long-run impact: It is important to note that the long-run and short-run effects of trade freedom on the ecological footprint in Belt and Road Initiatives (BRI) countries can vary from country to country. Each Belt and Road Initiative (BRI) country has its dynamic situation. The steps each country takes to limit environmental harm through implementing regulations may affect the total effects of free trade on the ecological footprint. The interaction of several factors, such as legal restrictions, technical advances, and public consumption of green products, would play a role in economic growth from a long-term sustainability perspective (Lin and Abudu, 2020). Besides this, it is essential to consider that every Belt and Road Initiative (BRI) nation is in its position, has distinct circumstances, is at different levels of government, and has its degrees of adhesion to sustainable development policy.

Various determinants, such as government legislation, new technological breakthroughs, and public and private sector commitment to sustainable practices, are significant elements shaping the long-term prospects of financial development consistent with environmentally responsible practices. This demonstrates that even in BRI countries, the impact of urbanization and environmental degradation in the city depends on the city and region. Reducing the ecological footprint of urbanization results from multiple factors such as urban design, infrastructure development, policy, and awareness among the masses. Integration of green urban development and planning is indispensable to avoid the environmental issues that may unfold in the future due to the acceleration of urbanization. On the other hand, politics, personal lifestyle choices, and, to some degree, a

person's economic status play a role in the environmental effect of a country's initiative. Although some of the early-day environmental issues will appear due to rising consumption and development, the final environmental implications will depend on how successful the management of financial inclusion is and the discussions on sustainable behaviors and investments. By developing an innovative strategy to enhance financial inclusion and regulatory frameworks, the business's ecological footprint can be reduced gradually (Sengupta et al., 2019; Dou et al., 2021). Reducing ecological footprint, the main element of implementing energy efficiency and sustainable development, is the core activity of countries participating in BRI. They address and solve the environmental problems of right now by saving energy and cutting the use of harmful substances. Therefore, technological advancements in nanotechnology can lead to long-term evolution for companies towards a healthier ecological development (Magazzino, 2016; Hardiyansah et al., 2021).

5.2 Conclusion

At the end of this study, several factors will be analyzed: trade openness, industrial production, urbanization, financial inclusion, and energy efficiency and their effect on environmental performance. This study collects data from 1991 to 2022. The relationship between trade freedom and environmental performance (ecological foot-point) Each Belt and Road Initiatives (BRI) country has its own set of circumstances, and the amount to which it implements regulations to limit environmental harm may impact the overall impact of trade freedom on the ecological footprint. However, the relationship between industrial production and environmental performance (ecological foot-point) is essential; each Belt and Roads Initiatives (BRI) country has distinct circumstances, policies, and levels of commitment to sustainable development, which define the entire impact of industrial production on the ecological footprint in those countries. Therefore, the relationship between urbanization and ecological foot-point. Sustainable urban development and planning are needed in Belt and Roads Initiatives (BRI) countries to offset the negative ecological effects of urbanization over time. The ecological effect of financial inclusion is carefully considered. Managing and altering financial inclusion to lead to benign behaviors and investments can have broader effects on the environment, even though more consumption and development may cause adverse environmental effects in the short term. Moreover, energy efficiency and ecological footprint share a strong relationship. Energy efficiency initiatives, which enable BRICS countries, are a crucial aspect in the Sustainable development of the BRI by reducing the ecological footprint.

5.3 Implications

5.3.1 Theoretical implications

The study examines the theoretical implications of Ecological Modernization Theory and Social Capital Theory on Belt and Road Initiative (BRI) countries. Ecological Modernization Theory focuses on aligning economic development with environmental sustainability, which is crucial for BRI nations to balance industrialization with environmental preservation. Social Capital Theory examines the role of social networks and relationships in shaping environmental performance within BRI countries. If stronger social capital, characterized by trust and cooperation, positively influences environmental practices, it could validate the theory's relevance in addressing environmental challenges. Policies promoting social capital and community engagement could enhance environmental performance.

Moreover, the investigation discusses people's social networks, which aid in accepting greener innovations and environmentally friendly practices. The study contests conventional frameworks through empirical analysis and offers refined interpretations and possibilities for different understandings of the evolutionary process. It incorporates theories from different fields and uses innovative techniques to provide a rounded framework for sustainability-related discussions in BRI economies.

5.3.2 Practical implications

This study of environmental performance within Belt and Road Initiative (BRI) countries under the influence of trade openness, industrial manufacturing, energy efficiency, urbanization, and financial initiative has functional, practical implications. It can recommend policymakers, pull investors' indicator strings, and shape BRI projects' behaviors to be eco-friendly. It can boost the volume of green finance and capacity in renewable sources and strengthen multilateral cooperation on solving transboundary environmental problems. Environmental conditions in BRI are ensured by undertaking routine ecological impact assessments during the project conducted and supporting local communities to make environmental and social benefits familiar. The research increases awareness among the public concerning the issue of striking a balance between economic development and environmental protection. Thus, BRI countries and all countries involved in the process will benefit. One of the fundamental prerequisites for identifying the objectives and imposing responsibilities is to achieve transparency and stakeholder confidence. On the other hand, it is through awareness of the underlying forces behind determining sustainable development and sustainability strategies over extended periods.

5.4 Limitations and future directions

The research has various limitations, such as insufficient data availability, reliability, and coverage; care for generalizations to other locations or the globe; and variable biases or measurement errors connected to financial inclusion, trade openness, industrial production, urbanization, and energy efficiency. The study is based on cross-sectional data, which may need revision to identify cause-and-effect patterns and trends. Longitudinal studies should be prioritized for future analysis, covering various aspects such as analysis of the same variables, identification of trends across the years, and assessment of all possible changes. Additionally, the limitations associated with analyzing BRI economies may require involvement from other countries and researchers. Qualitative analysis and investigation of policy,

technology, or institutional backgrounds may help identify more important factors.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

MR: Conceptualization, Data curation, Writing–original draft, Formal analysis, Funding acquisition, Investigation. MN: Conceptualization, Data curation, Writing–original draft, Formal analysis, Funding acquisition, Investigation. MA: Investigation, Methodology, Project administration, Resources, Writing–review and editing. YA: Investigation, Methodology, Project administration, Resources, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Unveiling the truth: greenwashing in sustainable finance

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Introduction: Greenwashing in sustainable finance involves misleading portrayals of investment products as environmentally friendly. This study explores the prevalence of greenwashing, its forms, impacts, and potential remedies. It underscores the need to align investor values with genuine environmental sustainability, emphasizing the pitfalls of greenwashing in sustainable finance.

Methods: The study employs a scoping review methodology guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. It involves systematically searching, selecting, and synthesizing evidence from various databases and sources to map critical concepts, types of evidence, and research gaps in greenwashing within sustainable finance.

Results: The study reveals diverse greenwashing strategies across industries, including ambiguous language, irrelevant claims, and opacity. It highlights greenwashing's severe consequences on corporate reputation, financial performance, and stakeholder trust. The effectiveness of regulatory bodies, Non-Governmental Organizations, and certifications in curbing greenwashing is discussed, though their effectiveness is debatable. The research also examines greenwashing's impact on investor behavior and decision-making.

Discussion: This research contributes to understanding greenwashing in sustainable finance, emphasizing vigilance, transparency, and accountability. It calls for more stringent regulations, international cooperation, and public awareness to combat greenwashing effectively. The study also suggests that businesses should adopt genuine and transparent environmental practices to avoid the risks of greenwashing, including legal repercussions. For future research, the study proposes a deeper exploration of the mechanisms enabling greenwashing and the effectiveness of different regulatory strategies and measures to combat it.

KEYWORDS

greenwashing, sustainable finance, ESG, sustainability, CSR, governance, social responsibility

1 Introduction

Greenwashing, a term coined in the 1980s, is a deceptive practice where a company or an organization spends more time and resources on marketing themselves as environmentally friendly and minimizing their environmental impact (Delmas and Burbano, 2011). It involves disseminating misleading information to create an overly optimistic image of the company's environmental practices or products. In sustainable finance, greenwashing refers to misrepresenting investment products as environmentally friendly when they are not, leading to a false perception of a company's commitment to environmental sustainability (Schneider-Maunoury, 2023).

Greenwashing can take various forms, such as vague language, irrelevant claims, false labels, and lack of transparency. For instance, a company might label its products as all-natural, green, or eco-friendly without providing any concrete evidence or certification to support these claims (Bowen and Aragon-Correa, 2014). Green bonds are a common area where greenwashing can occur in sustainable finance. These are bonds where the proceeds are used to fund environmentally friendly projects. However, companies can mislead investors about using funds without proper regulation and transparency, leading to greenwashing (Karpf and Mandel, 2017).

Real-life examples of greenwashing in sustainable finance are common. For instance, Volkswagen, a prominent automobile company, admitted to cheating emissions tests by fitting various vehicles with a "defect" device. This device could detect when the car was undergoing an emissions test and alter the performance to reduce emissions. This scheme happened while the company publicly touted its vehicles' low-emissions and eco-friendly features in marketing campaigns (Robinson, 2023).

For several reasons, the study of greenwashing in sustainable finance is paramount in the current context. First, with the increasing awareness and concern about environmental issues, more investors seek to align their investment decisions with their ecological values (Richardson and Cragg, 2010). This alignment has led to a surge in demand for sustainable investment products. However, the lack of standardization and regulation in what constitutes a green or sustainable investment has created an environment ripe for greenwashing (Bauer and Hann, 2010).

Second, greenwashing can undermine the credibility of the sustainable finance market and hinder the transition to a low-carbon economy. If investors cannot trust the environmental claims made by companies, they may become reluctant to invest in sustainable products, slowing the flow of capital to genuinely sustainable projects (Gillenwater, 2008).

Third, greenwashing can lead to an inefficient allocation of resources. Investors need to be more informed about directing their funds toward sustainable projects. In contrast, projects that could make a real difference in environmental impact need to be noticed (Kozlowski et al., 2015).

An illustrative example that underscores this study's significance is the case of the multinational investment bank JP Morgan Chase. In 2020, the Rainforest Action Network (RAN) reported that JP Morgan Chase was the world's leading financier of fossil fuels despite its claims of being a leader in sustainable finance. The bank has provided over $268 billion in financing to fossil fuel companies since the Paris Agreement was signed in 2016, contradicting its public commitment to sustainability and climate change mitigation (RAN, 2020). This case highlights the urgent need for increased transparency and regulation in sustainable finance to prevent greenwashing and ensure investors' funds genuinely contribute to environmental sustainability.

This research aims to answer the following questions:

- What are the prevalent forms of greenwashing in sustainable finance, and how do they manifest in different sectors?
- How does greenwashing affect the credibility and functioning of the sustainable finance market?
- What are the potential measures to combat greenwashing in sustainable finance, and how effective are they?
- How does greenwashing in sustainable finance affect investor behavior and decision-making?

These questions are designed to provide a comprehensive understanding of greenwashing in sustainable finance, its implications, and potential solutions. For instance, a study by Cosgrove et al. (2023) emphasizes robust, science-based metrics and cost-effective data collection and monitoring systems to safeguard sustainable finance against greenwashing. This research topic aligns with our research question on potential measures to combat greenwashing.

The significance of this article within the broader framework of the United Nations Sustainable Development Goals (SDGs) provides a vital perspective on its significance and impact. The article explores greenwashing in sustainable finance directly aligning with several SDGs, particularly Goal 12: Responsible Consumption and Production and Goal 13: Climate Action. By scrutinizing the prevalence and consequences of greenwashing, this research contributes to a deeper understanding of how deceptive environmental claims can undermine efforts toward sustainable consumption and production patterns, as highlighted in SDG 12. It underscores the critical need for transparency, accountability, and genuinely sustainable practices in financial investments to ensure that they contribute effectively to environmental sustainability.

Moreover, the study's focus on sustainable finance as a vehicle for combating greenwashing resonates with the urgent objectives of SDG 13, which calls for immediate action to combat climate change and its impacts. By revealing the intricate dynamics of greenwashing within the sustainable finance sector, this study illuminates the challenges and opportunities in directing financial flows toward truly sustainable projects that can mitigate climate change. This alignment with the SDGs emphasizes the article's relevance to global sustainability efforts, highlighting the importance of rigorous, science-based approaches for achieving a sustainable and resilient future. Through this lens, the article not only contributes to academic discourse but also to the practical and policy-oriented efforts aimed at realizing the United Nations' vision for a sustainable world.

Our study's investigation into the intricate dynamics of greenwashing within sustainable finance is significant and relevant to a global audience. It transcends geographical, cultural, and economic boundaries as the world grapples with the escalating challenges of climate change, resource depletion, and social inequality. The role of finance in fostering sustainable development has never been more critical. This article sheds light on how deceptive greenwashing practices can undermine the integrity of sustainable finance, mislead stakeholders, and divert resources away from genuine sustainability projects. By offering a comprehensive analysis of greenwashing practices, their impact on investor trust, and the effectiveness of regulatory frameworks in various contexts, this research provides valuable insights for policymakers, investors, academics, and practitioners worldwide. It invites a global dialog on enhancing transparency and accountability in sustainable finance, making it an indispensable resource for anyone committed to advancing environmental sustainability and social responsibility across the globe. Our findings and discussions are both timely and crucial for informing global efforts to align financial mechanisms with the broader goals of sustainable development, making our study an essential contribution to the worldwide discourse on sustainable finance.

The structure of this paper is designed to systematically explore and dissect the multifaceted issue of greenwashing within sustainable finance. Following this introduction, the **Methods** section delineates the scoping review methodology adopted, employing the PRISMA framework to ensure a thorough and systematic analysis of relevant literature, mapping out the key concepts, types of evidence, and research gaps related to greenwashing in sustainable finance. The **Results** section presents a synthesis of the findings from the scoping review, revealing the diversity of greenwashing strategies, their consequences, and the debatable effectiveness of various actors like regulatory bodies and Non-Governmental Organizations (NGOs) in mitigating these practices. This section also delves into how greenwashing influences investor behavior and decision-making processes.

In the **Discussion** segment, we critically examine the implications of our findings, emphasizing the necessity for increased vigilance, transparency, and accountability to combat greenwashing effectively. This part argues for enhanced regulations, international cooperation, and heightened public awareness as indispensable measures to counteract greenwashing. We also discuss businesses' responsibility to adopt transparent and genuine environmental practices to mitigate the risks of greenwashing, including legal repercussions. The **Conclusion** consolidates our study's insights, summarizing the pervasive nature of greenwashing across sectors, its impact on corporate reputation and stakeholder trust, and the urgent need for more effective strategies to combat it. Finally, we outline the limitations of our study and propose directions for future research, mainly focusing on exploring the mechanisms enabling greenwashing and assessing the efficacy of different regulatory and preventative measures.

2 Methods

This study uses a scoping review methodology to explore greenwashing in sustainable finance. A scoping review is a form of knowledge synthesis that addresses an exploratory research question aimed at mapping key concepts, types of evidence, and research gaps related to a defined area or field by systematically searching, selecting, and synthesizing existing knowledge (Arksey and O'Malley, 2005). This methodology is beneficial for complex or emerging evidence, such as greenwashing in sustainable finance, where many different study designs might be applicable.

The scoping review methodology is guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) Extension for Scoping Reviews (PRISMA-ScR) (Tricco et al., 2018). This framework provides a rigorous and transparent approach to conducting scoping reviews, ensuring that the process is replicable and the findings are reliable.

The scoping review methodology is appropriate for this study as it allows for a broad exploration of the concept of greenwashing in sustainable finance. It enables the identification of the primary sources and types of evidence available, examining how research on this topic is conducted, and understanding the key findings in the field. This methodology also allows for identifying gaps in the existing literature, which can inform future research directions (Cosgrove et al., 2023).

Identifying relevant literature involves systematically searching multiple databases and sources to ensure a comprehensive review of the evidence. The search strategy aims to answer the research question and includes a combination of keywords and Boolean operators to capture all relevant studies. The search is conducted in databases such as PubMed, Web of Science, IEEE Xplore, Scopus, Google Scholar, ACM Digital Library, ScienceDirect, JSTOR, ProQuest, SpringerLink, EBSCOhost, ERIC. The examined databases also included Business Source Complete, Emerald Insight, SAGE Journals, Social Science Research Network (SSRN), Wiley Online Library, Taylor & Francis Online, CAB Abstracts, ResearchGate, Oxford Academic Journals, Nature Research, EconLit, GreenFILE, PsycINFO, Philosopher's Index, AGRIS, LexisNexis Academic, Directory of Open Access Journals (DOAJ), and BioOne. The explored databases also comprised WorldWideScience, Social Sciences Citation Index, CINAHL, Project MUSE, Agricola, Environmental Sciences and Pollution Management, PAIS Index, Zetoc, The Sustainability Science Abstracts, Eldis, SAO/NASA Astrophysics Data System, Inspec, ArXiv, OpenGrey, Environmental Science Database, Sociological Abstracts, AgEcon Search, Oceanic Abstracts, Transport Research International Documentation, and Biodiversity Heritage Library.

A meticulously crafted search strategy was employed across the databases listed above to capture the relevant literature for our study. This strategy combined keywords related to the core themes of greenwashing and sustainable finance alongside Boolean operators to refine the search results. The primary keywords included 'greenwashing,' 'sustainable finance,' 'ESG (Environmental, Social, and Governance),' 'sustainability,' 'CSR (Corporate Social Responsibility),' and 'governance.' These terms were paired with Boolean operators to expand, limit, or define the search. For instance:

The term 'greenwashing' was combined with 'sustainable finance' using the AND operator (greenwashing AND sustainable finance) to identify literature directly addressing greenwashing within sustainable finance.

To encompass broader discussions related to environmental and social governance, the OR operator was employed, linking ESG-related terms (ESG OR environmental social governance OR sustainability OR CSR).

The NOT operator was used sparingly to exclude irrelevant results, such as articles focusing solely on generic marketing strategies without a direct link to environmental claims (e.g., marketing NOT greenwashing).

Additionally, specific phrases were enclosed in quotation marks to ensure that the search engines retrieved articles where these terms appeared as exact phrases, enhancing the relevance of the search results. For example, "corporate social responsibility" and "environmental sustainability" were quoted to target literature discussing these precise concepts.

The search was refined by including filters for peer-reviewed articles, reports, and grey literature to ensure the sources' academic rigor and relevance. This comprehensive and iterative approach, combining keywords and Boolean operators, facilitated a thorough and systematic exploration of the existing body of knowledge on greenwashing in sustainable finance. This strategy was designed to be inclusive, capture a broad spectrum of relevant literature, and be precise, minimizing the inclusion of tangential or unrelated studies.

The criteria utilized to include or exclude literature in our study followed a rigorous and systematic approach guided by the PRISMA framework explained above to ensure a comprehensive and relevant review of existing knowledge. The inclusion criteria included the following:

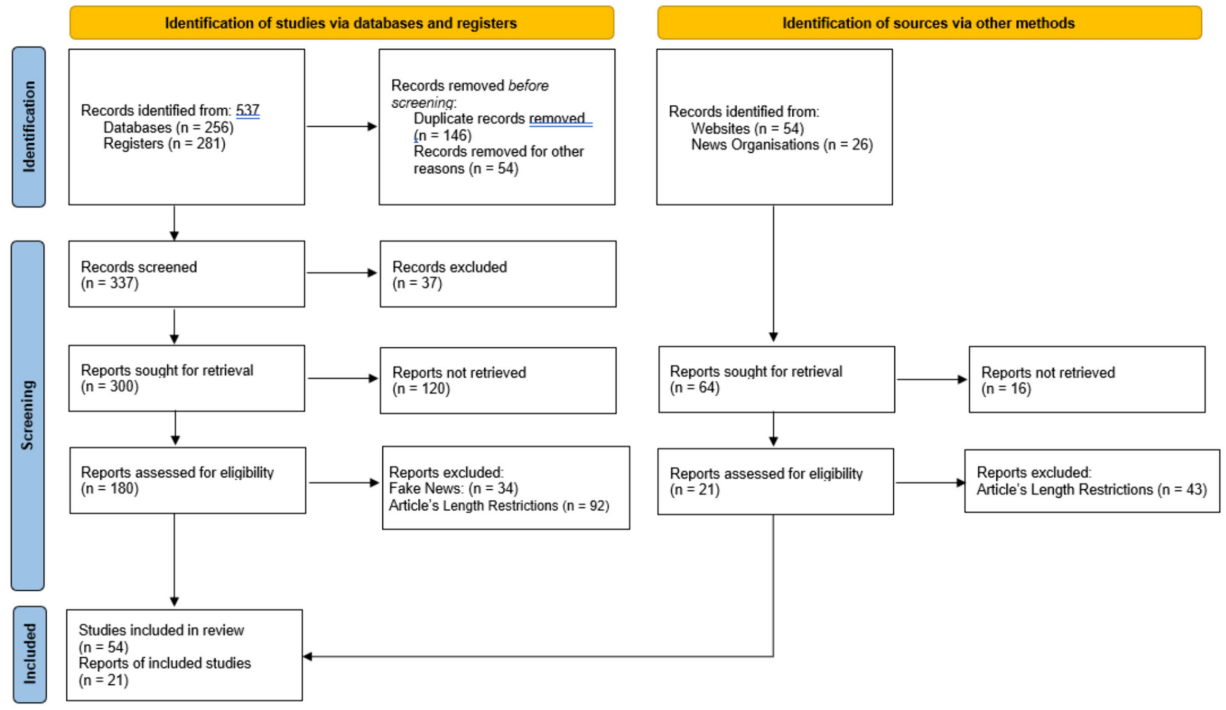


FIGURE 1
PRISMA flow diagram. Source: Page et al. (2021). http://www.prisma-statement.org/.

- Topical Relevance: Articles, reports, and grey literature that directly addressed the phenomena of greenwashing within the context of sustainable finance were included. This relevance was determined by examining abstracts and keywords, focusing on studies exploring the strategies, impacts, and remedies of greenwashing.
- Publication Date: Given the evolving nature of sustainable finance and greenwashing practices, recent publications from the last two decades (2004–2024) were prioritized to ensure the most current understanding of the topic.
- Peer-Reviewed Articles: Priority was given to peer-reviewed journal articles to maintain academic rigor and credibility. However, significant reports and grey literature from reputable sources were also considered to capture a broad spectrum of insights and perspectives.
- Language: The search was limited to literature published in English to ensure the feasibility of the research team's thorough analysis.
- Availability: Articles that were accessible in full-text form and could be retrieved through database subscriptions, open access, or institutional sources were included to ensure a detailed review of the content.

The exclusion criteria comprised the following:

- Irrelevance to Sustainable Finance: Studies that mentioned greenwashing in contexts unrelated to finance, such as pure marketing strategies or product labeling without a clear link to investment or financial products, were excluded.
- Outdated Studies: Older studies, while potentially valuable historically, were excluded to maintain a focus on the current state of greenwashing within sustainable finance.
- Non-English Literature: Articles not published in English were excluded due to the language capabilities of the research team.
- Incomplete or Abstract-only Publications: Studies for which only abstracts were available or incomplete were excluded, as these did not provide sufficient detail for analysis.
- Duplicate Studies: To ensure a unique dataset, duplicates or multiple reports of the same study across different databases were identified and excluded.

This strategic approach to inclusion and exclusion ensured the compilation of a comprehensive, relevant, and up-to-date dataset that forms the basis for analyzing the prevalence, forms, and impacts of greenwashing in sustainable finance, along with potential remedies.

The search strategy was iterative, refined, and adjusted as new relevant studies were identified. Hand-searching reference lists of included studies also supplemented the search and pertinent reviews to identify any additional studies that may have been missed in the database search (Mishra et al., 2023).

Figure 1 delineates the article selection process, detailing the initial identification, exclusions based on title and abstract, and further exclusions following a full-text review. It also presents the final count of articles included in the analysis and the rationale for exclusion at each stage. In the first phase, labeled as "Identification of sources via other methods," we identified 80 records, which included 54 from various online platforms and 26 from institutional sources. Out of these, we aimed to retrieve 64 papers, while the remaining 16 were disregarded, as they needed to meet the inclusion criteria. We successfully retrieved 31 records, and after assessing their eligibility, we excluded 33 due to the constraints of article length, resulting in 31 articles being incorporated into the review.

In the second phase, "Identification of studies via databases and registers," we initially identified 537 records, with 256 documents from various databases and 281 records from registers. Before the screening process, we eliminated 200 papers: 146 due to duplication and 54 for miscellaneous reasons. This selection left us with 337 records for screening, from which 37 were excluded, as they needed to meet the inclusion criteria. We aimed to retrieve 300 papers post-screening, but 120 were not retrieved due to the exclusion criteria. We assessed the eligibility of the remaining 180 records, and 126 were excluded: 34 were identified as misinformation, and 92 due to the article's length restrictions. This screening included 54 articles from the databases and registers and 21 from alternative sources, resulting in 75 secondary sources for our analysis.

Once the relevant literature is identified, it is analyzed and synthesized to answer the research question. This process involves extracting data from the included studies, such as study characteristics, methods, and critical findings. The data extraction process is systematic and is guided by a predefined data extraction form to ensure consistency.

The extracted data is then synthesized to provide an overview of the evidence. The synthesis can involve a narrative description of the findings, thematic analysis, or a combination of both, depending on the nature of the evidence. The synthesis provides insights into the concept of greenwashing in sustainable finance, including its forms, tactics, impacts, and the strategies companies use to engage in greenwashing (Khmyz, 2023).

Our thematic analysis is a method of synthesizing extracted data alongside or as an alternative to narrative descriptions. This methodological approach is tailored to the nature of the evidence collected. This pertains to our qualitative research methodology employed to detect, examine, and present patterns (themes) within the data. It offers an in-depth and sophisticated comprehension of the data's substance and foundational ideas or notions.

By employing thematic analysis, we aimed to distill complex information from various sources into coherent, significant themes related to greenwashing practices, their prevalence, impacts, and the effectiveness of existing measures to combat them. This approach allowed us to explore variations and commonalities across the reviewed literature, offering insights into the mechanisms of greenwashing and the multifaceted responses to it within the sustainable finance sector. It also facilitated the identification of gaps in the current body of knowledge and future research efforts toward unexplored or underexplored areas. This approach was particularly suitable for our study's scope, given its flexibility and applicability to various datasets. It enables a comprehensive synthesis of evidence on a relatively emerging and complex phenomenon like greenwashing in sustainable finance.

The key themes related to greenwashing in sustainable finance considered relevant to writing our article included the following:

- Forms and Tactics of Greenwashing: Corporations employ varied tactics to seem more eco-friendly than they are, including the use of ambiguous terminology, unrelated assertions, and improper application of certifications.
- Drivers of Greenwashing: Factors motivating companies to engage in greenwashing, including the desire to enhance corporate image, respond to stakeholder pressures, and comply with minimal regulatory requirements.
- Impacts on Corporate Reputation and Financial Performance: Greenwashing has short-term and long-term consequences for a company's reputation among consumers and investors and financial outcomes.
- Stakeholder Perceptions and Behavior: How greenwashing influences the perceptions and behaviors of different stakeholders, including consumers, investors, and regulatory bodies, and their trust in sustainable finance products.
- Regulatory Responses and Effectiveness: This theme encompasses the role of governmental and regulatory bodies in establishing standards, promoting transparency, and enforcing compliance to combat greenwashing and the effectiveness of these measures.
- Role of Non-Governmental Organizations (NGOs) and Institutions: NGOs and institutions contribute to advocating for stronger regulations, raising public awareness, and promoting genuine environmental practices.
- Third-Party Certifications and Eco-Labels: How independent certifications and eco-labels can help mitigate greenwashing by verifying companies' environmental claims and providing credible information to stakeholders.
- Sector-Specific Examples of Greenwashing: This theme includes instances of greenwashing practices within different sectors, such as automotive, fashion, and energy, illustrating the pervasiveness and variety of greenwashing tactics.
- Challenges and Limitations: Obstacles to effectively combating greenwashing, including regulatory limitations, enforcement challenges, and the complexity of assessing environmental impact.
- Future Directions and Research Needs: This theme highlights areas where further research is needed to better understand, prevent, and respond to greenwashing in sustainable finance, highlight gaps in current knowledge, and suggest new investigative avenues.

These themes, derived from thematic analysis, likely provided a structured framework for discussing greenwashing in sustainable finance, allowing the authors to address the phenomenon's complexity and multifaceted nature systematically.

Therefore, the scoping review methodology provides a rigorous and systematic approach to exploring greenwashing in sustainable finance. It allows for a comprehensive and in-depth understanding of the topic, informing both theory and practice in the field.

3 Literature review

The phenomenon of greenwashing in sustainable finance has been extensively studied in the literature. Delmas and Burbano (2011) provide a comprehensive analysis of the drivers of greenwashing, highlighting the role of internal and external factors. They argue that companies engage in greenwashing for various reasons, including enhancing their corporate image, responding to stakeholder pressures, and complying with regulatory requirements. Similarly, Walker et al. (2008) explore the drivers and barriers to environmental supply chain management practices, a key area where greenwashing can occur. They find that while significant incentives exist for companies to adopt green practices, substantial barriers exist, including cost and lack of legitimacy.

The impact of greenwashing on corporate reputation and financial performance has also been a significant research focus. For instance,

Lyon and Wren Montgomery (2015) find that greenwashing can harm a company's reputation, leading to loss of consumer trust and potential financial penalties. On the other hand, Parguel et al. (2011) argue that greenwashing can sometimes enhance a company's financial performance by attracting environmentally conscious consumers and investors. However, this effect will likely be short-lived as consumers become more aware of the company's deceptive practices.

The role of stakeholders in greenwashing is another crucial theme in the literature. According to Seele and Gatti (2017), stakeholders, particularly consumers and investors, play a vital role in enabling or discouraging greenwashing. They suggest that stakeholders' perceptions and responses to greenwashing can significantly influence a company's strategies. Du et al. (2010), who find that consumers' perceptions of a company's CSR practices can significantly influence their responses to greenwashing, echo this.

The literature also provides valuable insights into the measures to combat greenwashing. For instance, Marquis et al. (2016) argue for more stringent regulation and standardization in sustainable finance to prevent greenwashing. They suggest that regulatory bodies should be more proactive in monitoring and enforcing compliance with environmental standards. Similarly, Mitchell et al. (2010) highlight the importance of education and awareness in combating greenwashing. They argue that consumers must be more informed about companies' environmental practices to make more sustainable choices.

The relationship between greenwashing and sustainable development is another critical area of research. According to Laufer (2003), greenwashing can undermine sustainable development by diverting resources from sustainable projects. He argues that greenwashing can create a false perception of sustainability, leading to inefficient allocation of resources. TerraChoice (2010), who finds that greenwashing can lead to cynicism and distrust, supports this among consumers, hindering the adoption of sustainable practices.

Regarding sector-specific analysis, the literature provides evidence of greenwashing across various sectors. For instance, Dauvergne and Lister (2010) examine the prevalence of greenwashing in palm oil, while Lyon and Maxwell (2011) focus on the automobile industry. These studies highlight the pervasive nature of greenwashing and the need for sector-specific strategies to combat it.

The intertwining of greenwashing and sustainable finance is a complex phenomenon that draws upon diverse perspectives, methodologies, and theoretical underpinnings (Netto et al., 2020; Yang et al., 2020). The relationship between technological innovations such as Fintech and sustainable finance is pivotal. Vergara and Agudo (2021) emphasize how digital financial solutions can enhance transparency and consumer protection, potentially mitigating greenwashing practices. This synergy is further explored through the lens of artificial intelligence, where Moodaley and Telukdarie (2023) underscore AI's capacity to scrutinize sustainability reports for signs of greenwashing, offering a novel pathway to bolster the credibility of corporate environmental disclosures.

Consumer perceptions play a critical role in the dynamics of greenwashing, as evidenced by Wodnicka's (2023) investigation into how greenwashing influences purchasing decisions, underscoring the necessity for clear communication and authentic sustainable practices. As proposed by Yildirim (2023), the dual nature of greenwashing introduces an intriguing dichotomy, suggesting that while certain practices may be deceptive, others could inadvertently propel companies toward genuine sustainability efforts. The adaptation of fraud accounting models to the realm of greenwashing by Kurpierz and Smith (2020) provides a novel framework to understand and address the issue within CSR reporting, highlighting the intricate relationship between fraud and greenwashing.

Within sustainable finance, the critique of current sustainability measurement methods for investment funds by Popescu et al. (2021) calls attention to the need for accurate reflection of real-world impacts and the facilitation of a transition to a low-carbon economy. The examination of green finance products within banks by Akomea-Frimpong et al. (2021) identifies critical determinants, such as environmental policies and regulations, that influence the adoption of green finance, emphasizing the banking sector's role in this regard. The significance of green investments for sustainable economic growth, as explored by Goel (2016), alongside the barriers to green finance adoption identified through the ISM study by Khan et al. (2022), underscores the complexities of integrating sustainability into the financial sector.

Salzmann (2013) provides a comprehensive overview of sustainability issues within financial research, advocating for the deeper integration of CSR into sustainable finance and outlining directions for future research. This call for integration is echoed in the bibliometric analysis conducted by Kashi and Shah (2023), which maps the landscape of sustainable finance research and identifies pivotal gaps and areas for further exploration.

The literature underscores a burgeoning interest in delineating, understanding, and countering greenwashing in sustainable finance yet reveals persistent gaps in the development of universally accepted standards, the role of regulatory frameworks, and the potential of technological advancements to foster transparency and authenticity. Addressing these gaps necessitates robust methodologies for assessing financial products' sustainability impact and scrutinizing the efficacy of regulatory measures against greenwashing. The call for multidisciplinary approaches and collaborative efforts among academics, policymakers, and practitioners is clear, underlining the collective endeavor required to navigate the complexities of greenwashing and cultivate a more sustainable financial ecosystem.

4 Corporate strategies and practices in greenwashing

Greenwashing tactics and techniques are diverse and often sophisticated, making it challenging for consumers and investors to discern genuine sustainability efforts from deceptive practices. One common tactic is using vague language, such as eco-friendly, green, or natural, without providing concrete evidence or certification to support these claims (Bowen and Aragon-Correa, 2014; Calma, 2023). Another technique is using irrelevant claims or false labels that may sound impressive but have little to do with the product's environmental impact. For instance, a company might boast about the energy efficiency of its production process while ignoring the ecological harm caused by its products or their disposal (Delmas and Burbano, 2011).

In sustainable finance, greenwashing can involve misrepresenting the environmental benefits of an investment product or using funds raised through green bonds. For example, a company might claim that the proceeds from a green bond are being used to fund renewable energy projects. However, the funds might be used for projects with questionable environmental benefits or general corporate purposes (Karpf and Mandel, 2017).

Real-life examples of greenwashing tactics abound. For instance, fashion brands like H&M, Zara, and Uniqlo were caught greenwashing. These brands contribute to the massive amounts of textile waste caused by the clothing industry. Similarly, BP, a fossil fuel giant, changed its name to Beyond Petroleum and added solar panels to its gas stations despite spending more than 96% of its annual budget on oil and gas. Nestlé, Coca-Cola, and Starbucks have also been accused of greenwashing for misleading claims about the recyclability of their products or the sustainability of their practices. JP Morgan Chase, Citibank, and Bank of America have been criticized financially for promoting green investment opportunities while lending enormous sums to industries that contribute significantly to global warming, such as fossil fuels and deforestation (Robinson, 2023). These examples illustrate companies' wide range of tactics and techniques to greenwash their products, services, and practices.

In the food and beverage industry, McDonald's made headlines in 2019 when it launched a campaign to reduce single-use plastics in its stores, focusing on replacing all plastic straws with recyclable paper alternatives. However, it was later revealed that the new paper straws were not recyclable, and their sourcing and manufacturing raised different sustainability questions (Akepa, 2021).

Royal Dutch Shell has faced several court cases in the energy sector due to greenwashing. Despite launching campaigns and interviews describing itself as committed to global net-zero programs, reducing carbon emissions, and helping the world fight global warming, Shell has continued exploring new oil and gas production opportunities. It has only devoted 1% of its spending to renewable energy (Koons, 2022).

In the consumer goods sector, Nestlé announced in 2019 that it had "ambitions" for its packaging to be 100% recyclable or reusable by 2025. However, environmental groups criticized the company for not releasing clear targets, a timeline to accompany its ambitions, or additional efforts to help facilitate consumer recycling. Nestlé, Coca-Cola, and PepsiCo were named the world's top plastic polluters for the third year (Robinson, 2023).

A recent study by Orazalin et al. (2023) found that companies often employ greenwashing tactics to create positive impressions among stakeholders and protect their legitimacy. The study also revealed that the impact of greenwashing varies across different sectors and periods. Another study by Madden (2022) argued that companies should focus on innovation rather than relying on Environmental, Social, and Governance (ESG) metrics to lead the transition to net-zero emissions. The study highlighted the complexity of navigating the path to net-zero emissions and the critical role of innovation in this process. Stridsland et al. (2023) also emphasized the importance of transparency in emission disclosure to prevent greenwashing. They argued that companies should use greenhouse gas inventories for accounting and decision support to enhance the green transition. These examples illustrate how greenwashing can manifest in different sectors, highlighting the need for consumers and investors to be vigilant and critical of companies' environmental claims.

Greenwashing can have significant implications for a company's reputation and financial performance. On the one hand, greenwashing can enhance a company's reputation by creating a positive image of its environmental practices and products. This enhancement can attract environmentally conscious consumers and investors, increasing sales and investment (Bénabou and Tirole, 2010). However, when the truth about a company's greenwashing practices is revealed, it can severely damage its reputation (Ibbetson, 2020). Consumers and investors may feel deceived and lose trust in the company, leading to declining sales and investment. This feeling can also result in legal repercussions, as companies can be held accountable for misleading environmental claims.

Moreover, greenwashing can directly impact a company's financial performance. A study by Goss and Roberts (2011) found that companies with poor CSR practices, which can include greenwashing, pay higher costs for bank loans. These higher costs suggest that banks perceive these companies as riskier, reflecting the potential financial consequences of greenwashing.

In addition to these academic findings, factual examples further illustrate the impact of greenwashing on corporate reputation and financial performance. For instance, the German car manufacturer Volkswagen suffered a significant blow to its reputation and a sharp drop in sales following the revelation of its emissions scandal in 2015. The scandal, which involved the company cheating on emissions tests, led to billions of dollars in fines and lawsuits, demonstrating the severe financial consequences of greenwashing (Ewing, 2015).

Another example is the British multinational oil and gas company BP, which faced a public backlash and legal challenges after it was revealed that the company had misled the public about its environmental practices. Despite its efforts to rebrand itself as a green company, BP's reputation was severely damaged, and it was forced to pay billions of dollars in fines and compensation for the environmental damage caused by its operations (Dempsey and Raval, 2019).

These examples underscore the potential risks and costs associated with greenwashing, highlighting the importance of genuine commitment to environmental sustainability for corporate reputation and financial performance.

5 The impact of greenwashing on stakeholder perceptions and behavior

Consumers' perceptions and responses to greenwashing can vary significantly, and these reactions can profoundly affect a company's reputation and financial performance. According to Bénabou and Tirole (2010), society's demands for individual and corporate social responsibility are becoming increasingly prominent. However, when companies engage in greenwashing, they can undermine these demands and create a sense of mistrust among consumers. This sentiment can lead to a decline in sales and damage the company's reputation.

Greenwashing can lead to losing trust among consumers seeking to align their buying decisions with their environmental values. When products are misrepresented as environmentally friendly, consumers may feel deceived and reluctant to buy these products (Bénabou and Tirole, 2010). A study by Walker et al. (2008) found several drivers and barriers to implementing green supply chain management practices. One of the barriers identified was the lack of legitimacy, which can be linked to greenwashing. When companies make false or misleading claims about their environmental practices, they can undermine their legitimacy and credibility in the eyes of consumers.

Moreover, a study by Barnett and Salomon (2012) found that the relationship between corporate social performance (CSP) and corporate financial performance (CFP) is U-shaped. This result suggests that companies with either low or high CSP have higher CFP than companies with moderate CSP. This finding could imply that companies engaging in greenwashing (resulting in a moderate CSP due to the discrepancy between their claims and actual practices)

might achieve a different financial performance than companies genuinely committed to environmental sustainability.

In terms of practical examples, the Swedish multinational clothing-retail company H&M launched 2017 a "Conscious" collection, claiming that the clothes were made with sustainable materials. However, the Norwegian Consumer Authority accused H&M of greenwashing, arguing that the company provided insufficient information about the sustainability of the clothes and misled consumers into believing that the clothes were more sustainable than they were. This case led to a public outcry and calls for boycotts of H&M (Bain, 2019).

The examples above highlight the potential consequences of greenwashing for consumer perceptions and responses, underscoring the importance of transparency and honesty in companies' environmental claims. Unfortunately, the legitimacy of corporate environmental policies often remains unchecked, as companies are not usually mandated by law to validate their environmental statements with third parties, leading stakeholders to question the actual implementation of these policies (Ramus and Montiel, 2005).

Similarly, investors are becoming increasingly aware of and concerned about environmental issues. As a result, they are seeking to align their investment decisions with their ecological principles. However, when companies engage in greenwashing, they can weaken these values and create a sense of distrust among investors. This perception can lead to a deterioration in investment and harm the company's name (Bénabou and Tirole, 2010).

Greenwashing can result in a loss of confidence among investors looking to support their financial decisions with their environmental values. When financial products are tainted as environmentally friendly, investors may feel betrayed and become unwilling to invest in these products. This sentiment can slow the investment in sustainable projects and hamper the conversion to a low-carbon economy (Bénabou and Tirole, 2010).

A study by Walker and Dyck (2014) found that institutional investors, such as pension funds and mutual funds, are more likely to invest in companies with strong environmental performance. However, when companies engage in greenwashing, they can undermine this preference and deter institutional investors. This aversion can significantly affect a company's capital access and financial performance.

Moreover, a study by Lourenço et al. (2012) found that investors respond negatively to greenwashing. The study found that companies that engage in greenwashing have lower stock market performance than those that do not. This finding suggests that investors are becoming more discerning and punishing companies engaging in deceptive environmental practices.

Regarding factual examples, the case of Deutsche Bank's funds arm, DWS, is illustrative. In 2023, DWS was accused of greenwashing by misleading investors about its "green" investments. The company, which manages 928 billion euros ($994 billion) in assets, faced significant backlash from investors and the public, leading to the resignation of its CEO (Reuters, 2022).

Another example is the case of Holland & Knight, a law firm that launched a "greenwashing mitigation" team in 2023. The team is aimed at advising companies accused of failing to live up to their own environmental goals, highlighting the increasing legal risks associated with greenwashing (Bloomberg Law, 2023).

These examples highlight the potential consequences of greenwashing for investor perceptions and responses, underscoring the importance of transparency and honesty in companies' environmental claims.

6 Policies and regulations

Regulatory bodies play a pivotal role in preventing greenwashing by establishing and enforcing standards for environmental claims, promoting transparency, and holding companies accountable for misleading practices. The first regulatory measure against greenwashing is the establishment of clear and stringent standards for environmental claims. These standards provide a benchmark against which companies' ecological practices can be assessed, making it more challenging to make false or misleading claims about their environmental performance (Delmas and Burbano, 2011). For instance, the European Union has developed a classification system for sustainable activities, the EU Taxonomy, to prevent greenwashing in the financial sector. The Taxonomy sets performance thresholds for economic activities to qualify as environmentally sustainable, providing a clear framework for companies and investors (EU Technical Expert Group on Sustainable Finance, 2020).

Regulatory bodies also promote transparency by requiring companies to disclose their environmental practices and impacts. This promotion can involve mandatory reporting of greenhouse gas emissions, water usage, waste generation, and other environmental indicators. Such disclosure requirements make it harder for companies to hide their environmental impacts and can deter them from engaging in greenwashing (Reid and Toffel, 2009). For example, the U.S. Securities and Exchange Commission (SEC) has issued guidance on disclosing climate change-related risks, encouraging companies to provide detailed and accurate information about their environmental performance (SEC, 2010).

Similarly, regulatory bodies hold companies accountable for greenwashing by imposing penalties for misleading environmental claims. This accountability may include fines, sanctions, and even legal action. Such enforcement actions can deter greenwashing, as they increase the costs and risks associated with deceptive environmental practices (Parguel et al., 2011). However, greenwashing remains a pervasive problem despite these efforts, suggesting that more than current regulatory measures may be required. More research is needed to understand the effectiveness of different regulatory strategies and to identify new approaches to combating greenwashing. For example, in 2021, the UK's Competition and Markets Authority (CMA) launched an investigation into misleading green claims in the fashion industry. The CMA examined whether clothing and textile brands were misleading consumers about the environmental impact of their products and whether their claims comply with consumer law (CMA, 2022).

Countries have adopted varying approaches to combat greenwashing, reflecting their unique legal, economic, and cultural contexts. We analyze anti-greenwashing regulations in some countries, including the United States, the European Union, and China.

The Federal Trade Commission (FTC) is crucial in combating greenwashing through its Green Guides in the United States. These guides, first introduced in 1992 and most recently updated in 2012, provide businesses with guidance on making environmental claims to avoid deceiving consumers. The Green Guides are not legally binding, but the FTC can take enforcement action against companies that engage in deceptive marketing practices, including greenwashing

(FTC, 2012). Despite these efforts, some critics argue that the Green Guides must be revised to prevent greenwashing due to their voluntary nature and lack of specific standards (Nyilasy et al., 2014).

In the European Union, the fight against greenwashing is primarily regulated through the Unfair Commercial Practices Directive (UCPD), which prohibits misleading and aggressive commercial practices. The UCPD applies to environmental claims and takes action against greenwashing. In addition, the EU has developed a classification system for sustainable activities, known as the EU Taxonomy, to prevent greenwashing in the financial sector. The Taxonomy sets performance thresholds for economic activities to qualify as environmentally sustainable, providing a clear framework for companies and investors (EU Technical Expert Group on Sustainable Finance, 2020). However, some critics argue that the UCPD and the EU Taxonomy need to be sufficiently enforced and that more specific standards and stricter enforcement are needed (Ibanez and Grolleau, 2008).

China has also taken steps to combat greenwashing. The Chinese government has implemented various policies and regulations to promote green development and prevent greenwashing. These include the Environmental Protection Law, which requires companies to disclose their environmental information, and the Green Securities Policy, which promotes green investment and requires listed companies to disclose their environmental risks. Despite these efforts, greenwashing remains a significant issue in China, partly due to weak enforcement of regulations and a lack of public awareness (Du, 2015; Yu et al., 2020).

To sum up, while several countries have implemented regulations to combat greenwashing, the effectiveness of these regulations varies. There is a need for more stringent standards, stricter enforcement, and greater public awareness to combat greenwashing effectively.

The effectiveness of current regulations in curbing greenwashing has been debated among scholars. For instance, Lyon and Wren Montgomery (2015) argue that while rules such as the Federal Trade Commission's Green Guides in the United States and the Unfair Commercial Practices Directive in the European Union provide a framework for companies to make environmental claims, their effectiveness is limited due to their voluntary nature and lack of specific standards. These regulations may encourage companies to engage in greenwashing, as the potential benefits of greenwashing, such as enhanced corporate image and increased sales, outweigh the risks of regulatory penalties.

Similarly, a study by Marquis et al. (2016) found that regulatory enforcement of environmental standards varies significantly across countries, affecting the prevalence of greenwashing. They argue that companies may be more likely to engage in greenwashing in countries with weak regulatory enforcement due to the lower risk of penalties. This view highlights the importance of solid regulatory enforcement in preventing greenwashing.

On the other hand, a study by Dauvergne and Lister (2010) suggests that regulations can effectively curb greenwashing if accompanied by other measures, such as public pressure and market incentives. They argue that rules alone may not deter greenwashing. Still, when combined with public scrutiny and the potential for market rewards for genuine environmental performance, they can create a powerful deterrent against greenwashing.

However, despite these regulations and enforcement actions, greenwashing remains a pervasive problem, suggesting that more than current measures may be required. More research is needed to understand the effectiveness of different regulatory strategies and to identify new approaches to combating greenwashing.

Alternatively, institutions and NGOs are crucial in combating greenwashing. They can contribute to this effort through various means, such as advocacy, education, research, and the development of standards and certifications.

Institutions, particularly those focused on environmental and sustainability issues, can exert influence by researching and developing guidelines and standards for sustainable practices. For instance, the International Organization for Standardization (ISO) has developed a series of standards (ISO 14020) that provide environmental labels and declaration guidelines. These standards aim to prevent misleading or unsubstantiated environmental claims, thereby reducing the incidence of greenwashing (ISO, 2020).

On the other hand, NGOs often play a more activist role, raising awareness about greenwashing and advocating for stronger regulations and enforcement. They can also provide valuable resources for consumers and investors to help them make informed decisions. For example, Greenpeace, an international environmental NGO, has been instrumental in exposing cases of greenwashing and pushing for greater transparency and accountability in corporate ecological practices (Greenpeace, 2020). Another example is the Rainforest Action Network (RAN, 2021), which has actively exposed greenwashing in the financial sector. In 2021, RAN (2021) published a report revealing that many major banks continued to finance fossil fuel projects despite their public commitments to sustainability. This advocacy work can help hold companies accountable and deter greenwashing.

In the academic sphere, Lyon and Wren Montgomery (2015) highlight the role of NGOs in monitoring corporate behavior and providing information to the public. They argue that NGOs can counter corporate power by exposing deceptive environmental claims and advocating for stronger regulations. Similarly, Marquis et al. (2016) emphasize the role of institutional investors in combating greenwashing. They argue that institutional investors, such as pension funds and mutual funds, can pressure companies to improve their environmental performance and avoid greenwashing.

Briefly, institutions and NGOs play a vital role in combating greenwashing. Through their research, advocacy, and educational efforts, they can help to promote transparency, accountability, and genuine commitment to sustainability in the corporate sector.

In the same way and by independently verifying a company's environmental claims, third-party certifications and eco-labels are critical in preventing greenwashing. Independent organizations assessing companies' environmental performance against predefined criteria award these certifications and labels. Providing a credible and recognizable symbol of ecological performance can help consumers and investors distinguish between genuine and deceptive environmental claims (D'Souza et al., 2007).

One of the critical benefits of third-party certifications and eco-labels is that they can reduce the information asymmetry between companies and consumers or investors. Companies often have more information about their environmental performance than consumers or investors, creating greenwashing opportunities. However, third-party certifications and eco-labels can level the playing field by providing reliable and accessible information about a company's environmental performance. These certifications can help consumers

and investors make informed decisions and deter companies from greenwashing (Dauvergne and Lister, 2010).

However, the effectiveness of third-party certifications and eco-labels in preventing greenwashing can depend on several factors. These include the credibility of the certifying organization, the rigor of the certification process, and the transparency of the certification criteria. If these factors are not adequately addressed, there is a risk that certifications and labels themselves could be used as a form of greenwashing (Ibanez and Grolleau, 2008).

In a study by Parguel et al. (2011), it was found that eco-labels could indeed help in reducing greenwashing. The study highlighted that when used correctly, eco-labels can provide a clear and credible signal of a product's environmental performance, assisting consumers in making more informed choices and discouraging companies from making misleading environmental claims.

For example, the Forest Stewardship Council (FSC, n.d.) certification is a globally recognized standard for responsible forest management. Companies that achieve FSC certification have met rigorous environmental and social norms, assuring consumers and investors that their products are not contributing to deforestation or exploitation of forest communities. However, it is essential to note that while such certifications can help prevent greenwashing, they are not guaranteed. Critics argue that FSC has had minimal impact on deforestation since there have been instances where FSC-certified companies were involved in illegal logging and greenwashing practices. The FSC's decision-making structure, lack of expertise in certifying agencies, and competition from industry-run forest-certifying organizations have contributed to these shortcomings (Conniff, 2018).

Another example is the Energy Star label, a widely recognized symbol of energy efficiency. Products that carry the Energy Star label have been independently certified to meet strict standards for energy efficiency set by the U.S. Environmental Protection Agency. This label helps consumers identify energy-efficient products and reduces the likelihood of greenwashing in the energy sector (Energy Star, 2023).

Third-party certifications and eco-labels can significantly prevent greenwashing by independently verifying environmental claims and reducing information asymmetry. However, their effectiveness depends on the certifying organization's credibility, the certification process's rigor, and the certification criteria's transparency.

7 Discussion

At the outset of our exploration into greenwashing within sustainable finance, we sought to unpack several intricately connected research questions, aiming to dissect the phenomenon's prevalence, its myriad forms, impacts, and potential avenues for remediation. These queries are inherently interwoven with the broader dialog on sustainable finance's credibility and operational dynamics amidst growing greenwashing concerns.

To elucidate, we embarked on a systematic scoping review, adhering to the PRISMA framework, which enabled us to navigate the literature about greenwashing methodically. This approach was instrumental in uncovering the diverse strategies employed across sectors to portray investment products as environmentally benign. Notably, our findings reveal a spectrum of greenwashing tactics, from the deployment of ambiguous language to outright opacity, which collectively undermine stakeholder trust, tarnish corporate reputations, and dilute the financial performance of entities implicated in such practices.

Our research questions aimed to chart the terrain of greenwashing within sustainable finance, scrutinizing its manifestations across different industry sectors. This goal was realized through an extensive review that spotlighted the severe ramifications of greenwashing, on the implicated corporations' standing and fiscal health and the broader integrity of the sustainable finance market. The analysis further delved into the roles played by regulatory entities, NGOs, and certification mechanisms in countering greenwashing, albeit acknowledging the mixed efficacy of these interventions.

In addressing the potential measures to mitigate greenwashing, our research illuminated a spectrum of strategies, underscored by a call for stringent regulatory frameworks, bolstered international cooperation, and heightened public consciousness. Significantly, this discourse invites businesses to embrace authentic environmental stewardship, thus navigating away from the pitfalls associated with greenwashing, including legal entanglements and reputational damage.

Lastly, the study delves into how greenwashing influences investor behavior and decision-making, revealing unearthed insights into the detrimental effects of greenwashing on investment patterns and highlighting a pressing need for greater transparency and veracity in environmental claims. Through the lens of comprehensive evidence synthesis, this discussion section seeks to bridge the research questions with their corresponding findings, thus contributing a nuanced understanding of greenwashing's multifaceted impacts on sustainable finance while paving the way for future scholarly endeavors in this domain.

The findings of this research have significant implications for both theory and practice. From a theoretical perspective, the study contributes to the growing literature on greenwashing in sustainable finance. It provides a comprehensive overview of the prevalent forms of greenwashing, their impact on the credibility and functioning of the sustainable finance market, and potential measures to combat greenwashing. The study also highlights the need for further research on the effectiveness of these measures and the role of different stakeholders in combating greenwashing.

From a practical perspective, the study offers valuable insights for various stakeholders, including government authorities, businesses, non-profit organizations, and investors. For government authorities, the findings underscore the importance of robust regulation and enforcement to prevent greenwashing. This prevention includes the development of clear and stringent standards for environmental claims, promoting transparency through mandatory disclosure requirements, and imposing penalties for misleading practices. The study also highlights the need for international cooperation in regulating sustainable finance to ensure consistency and effectiveness across different jurisdictions.

For businesses, the study emphasizes the risks and costs associated with greenwashing, including damage to corporate reputation, loss of consumer and investor trust, and potential legal repercussions. It suggests businesses adopt genuine and transparent environmental practices to avoid these risks and gain a competitive advantage. As Lyon and Maxwell (2011) noted, companies that engage in greenwashing may experience short-term gains. Still, they will face long-term costs as consumers and investors become more discerning and regulatory scrutiny increases.

The study highlights non-profit organizations and NGOs' crucial role in combating greenwashing. These organizations can contribute

to this effort through advocacy, education, research, and the development of standards and certifications. They can also be vital in monitoring corporate behavior and providing public information, as Dauvergne and Lister (2010) suggested.

The study underscores the importance of vigilance and critical evaluation of companies' environmental claims for consumers and investors. As Walker and Dyck (2014) noted, consumers and investors are becoming increasingly aware of and concerned about environmental issues. They are seeking to align their financial decisions with their ecological values. However, the prevalence of greenwashing in sustainable finance can undermine these values and create a sense of mistrust. Therefore, consumers and investors must be equipped with the knowledge and tools to discern genuine sustainability efforts from deceptive practices.

In brief, the study provides a comprehensive understanding of greenwashing in sustainable finance, its implications, and potential solutions. It underscores the importance of transparency, accountability, and commitment to environmental sustainability in the corporate sector. It also highlights the need for further research and action to combat greenwashing and promote sustainable finance.

Our study delineated various forms of greenwashing prevalent in sustainable finance, highlighting the disconnect between advertised environmental stewardship and actual corporate practices. These findings beckon a deeper interrogation into the subtleties of greenwashing tactics, urging future research to explore the psychological and sociological dimensions that underpin corporate propensity toward such misleading practices. Moreover, this exploration into the forms and impacts of greenwashing uncovers a broader spectrum of theoretical implications, suggesting that greenwashing not only dilutes the essence of CSR but also signifies a fundamental misalignment between market incentives and environmental ethics.

One critique of our study centers on the scope and depth of the literature review. While extensive, our review may only partially capture the evolving landscape of greenwashing tactics amidst rapidly changing regulatory and technological environments. This limitation suggests a potential oversight of emerging greenwashing practices that are yet to be widely reported or scrutinized within academic circles. Furthermore, our analysis predominantly hinges on secondary data, which, while comprehensive, might not capture the nuanced motivations behind corporate greenwashing practices or the subjective interpretations of stakeholders encountering such practices.

Another limitation pertains to the geographical and sectoral scope of our study. Given the global nature of sustainable finance, our focus on predominantly Western corporations and financial markets may not adequately represent greenwashing practices and their implications in emerging markets or specific industries with unique environmental impacts and regulatory contexts.

Future research venues that can be derived from our study include, but are not limited to, the following:

- Emerging Greenwashing Practices: Subsequent research might investigate greenwashing within digital platforms and social networks, where disseminating corporate sustainability claims and stakeholder engagement presents new challenges and opportunities for greenwashing.
- Cross-Cultural and Sectoral Analysis: Research could extend to non-Western contexts and diverse industries, examining how cultural, regulatory, and market dynamics influence greenwashing practices and stakeholder perceptions.
- Motivational Analysis: Qualitative research examining the motivations of executives and marketers in pursuing greenwashing tactics could provide deeper insights into the phenomenon, potentially uncovering psychological and organizational factors at play.
- Impact of Technological Solutions: Investigating the role of emerging technologies (e.g., blockchain, AI) in detecting and mitigating greenwashing offers a promising avenue for research, addressing both practical and theoretical implications.

The theoretical implications of our findings extend beyond identifying and mitigating greenwashing to encompass broader discussions about the ethics of corporate sustainability practices, the role of transparency in sustainable finance, and the dynamics between corporate behavior, stakeholder perceptions, and regulatory responses.

Firstly, our study contributes to the discourse on CSR by highlighting the tension between genuine CSR initiatives and greenwashing practices. This tension invites a reevaluation of CSR theories to incorporate mechanisms for distinguishing between authentic and superficial environmental efforts (Bazillier and Vauday, 2015).

Secondly, the findings underscore the need for a theoretical framework that integrates stakeholder theory with concepts of legitimacy and trust. By examining how greenwashing erodes stakeholder trust and undermines the legitimacy of corporate environmental claims, future research can develop more nuanced understandings of stakeholder engagement in sustainable finance.

Lastly, our study prompts a theoretical exploration of regulatory effectiveness in combating greenwashing. The varied success of existing measures in different jurisdictions and sectors calls for a comparative analysis grounded in regulatory theory, exploring the conditions under which regulations effectively deter greenwashing and foster genuine sustainability practices.

In other words, while our study informs the pervasive issue of greenwashing in sustainable finance, its limitations pave the way for future research endeavors. By critically examining these limitations and proposing specific avenues for investigation, we can deepen our theoretical and practical understanding of greenwashing and its implications for sustainable finance.

The critical analysis of our results underscores the multifaceted repercussions of greenwashing, extending beyond the immediate corporate sphere to implicate the sustainable finance market at large. The deterioration of stakeholder trust and the erosion of market credibility underscore the need for a theoretical framework that reconciles the pursuit of financial gains with genuine environmental commitment. In this vein, our findings advocate for a paradigm shift in how environmental claims are construed, verified, and integrated within corporate strategies, heralding a new avenue of research examining current regulatory structures' efficiency and the possibility of novel governance approaches to curb greenwashing.

Furthermore, our investigation into the potential measures to combat greenwashing reveals a significant gap in the current understanding of regulatory and voluntary mechanisms' efficacy. This gap signals an emergent research domain that critically evaluates the interplay between policy instruments, corporate behavior, and stakeholder activism in fostering a more transparent

and accountable sustainable finance ecosystem. It further emphasizes the theoretical void concerning the function of technology and data analysis in improving the identification and prevention of greenwashing tactics.

Our discussion transcends the practical implications of combating greenwashing to probe its theoretical underpinnings and broader societal implications. By situating our findings within the existing corpus of knowledge, we underscore the exigency of addressing greenwashing and chart a course for future scholarly inquiry that bridges theoretical gaps and fosters a more sustainable integration of environmental imperatives within the finance sector. This reflection reinforces the study's contribution to advancing the discourse on sustainable finance and greenwashing.

8 Conclusion

The phenomenon of greenwashing in sustainable finance is a complex and multi-faceted issue. It manifests in various forms, from vague language and irrelevant claims to false labels and lack of transparency. This study has highlighted the prevalence of greenwashing across different sectors, with real-life examples from companies like Volkswagen, H&M, Zara, Uniqlo, BP, Nestlé, Coca-Cola, Starbucks, JP Morgan Chase, Citibank, and Bank of America.

The impact of greenwashing on corporate reputation and financial performance is significant. While it may initially enhance a company's reputation, the eventual revelation of deceptive practices can lead to severe damage, loss of trust, decline in sales and investment, and legal repercussions. This disclosure was evident in the cases of Volkswagen and BP, which faced substantial fines and lawsuits due to their greenwashing practices.

Greenwashing also affects stakeholder perceptions and behavior. Consumers and investors, increasingly aware of environmental issues, can feel deceived when companies engage in greenwashing, leading to a loss of trust and reluctance to invest in misrepresented products. This deception was illustrated in the cases of H&M and Deutsche Bank's funds arm, DWS (Reuters, 2022).

Regulatory bodies, institutions, NGOs, and third-party certifications play crucial roles in preventing greenwashing. However, their effectiveness varies, and greenwashing remains a pervasive problem, suggesting that more than current measures may be required.

This study has some limitations. First, while it provides a comprehensive overview of greenwashing in sustainable finance, it must delve deeper into the mechanisms and processes that enable greenwashing. Second, the study relies heavily on secondary data and factual examples, which may not fully capture the complexity and nuances of greenwashing practices. Third, the study needs to provide a detailed analysis of the effectiveness of different regulatory strategies and measures to combat greenwashing.

Future research could focus on developing a more nuanced understanding of the mechanisms and processes that enable greenwashing. This approach could involve in-depth case studies of specific companies or sectors. Research could also explore the effectiveness of different regulatory strategies and measures in combating greenwashing, including a comparative analysis of regulations in other countries. Additionally, the study could examine the role of consumers and investors in combating greenwashing, including their awareness, perceptions, and responses to greenwashing practices.

Understanding greenwashing in sustainable finance is crucial for promoting genuine environmental sustainability. Greenwashing undermines the credibility of the sustainable finance market and hinders the transition to a low-carbon economy. By shedding light on the prevalence, implications, and potential solutions to greenwashing, this study contributes to the ongoing efforts to ensure that sustainable finance lives up to its promise of driving environmental sustainability.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JD: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. EA: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. PM: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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The authors declare that the research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2024.1362051/full#supplementary-material

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Analysis of green deal communication on twitter: environmental and political perspective

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The Green Deal and its implementation are generating discussions across society. Changes brought about by the agreement could impact sustainable development worldwide; therefore, identifying the most common Green Deal-related topics on a global scale can offer insight into the public mood around implementation of the agreement. Social networks provide the opportunity to find such topics because they contain a large amount of data produced by users worldwide: analysis of their content can therefore provide insight into the discourse on the Green Deal and identify the sentiment in discussions around this topic. In this article, we present perceptions of the Green Deal and identify the main Green Deal-related topics based on analysis of communication on the Twitter social network (currently X social network). Using the search terms "green deal," "greendeal," and "#greendeal," 192,567 tweets from 89,328 unique users were captured between 1 January 2019 and 31 March 2023. We identified the 40 most used unique hashtags that people used when communicating about the Green Deal, which included "#EU," "#eugreendeal," and "#climatechange," and the 16 most relevant topics discussed in relation to the Green Deal, which included both European ("European Green Deal") and North American ("Green New Deal") perspectives. Each topic was associated with a certain amount of negative, positive, or neutral sentiment: the most positive sentiment was associated with the "Industrial plan" and "Hydrogen" topics, and the most negative sentiment was associated with topics relating to "Joe Biden" and "Alexandria Ocasio-Cortez." Overall, our analysis of the discourse regarding the Green Deal offers organizations and decision-makers insight into how people perceive different aspects of the Green Deal and related topics. This may be beneficial in tackling disinformation across social networks and increasing public awareness, which could create a society better equipped to face the global concern of climate change.

KEYWORDS

Green Deal, climate change, environment, sustainability, social media analysis, Twitter, X

1 Introduction

Climate change and other environmental shifts present significant challenges to global economies, societies, and ecosystems; this has necessitated urgent measures to secure environmental stability and prevent socio-ecological decline (Aguiar et al., 2018; He and Silliman, 2019; Barry and Hoyne, 2021; Persson et al., 2022; Hereu-Morales et al., 2023). Specifically, over the past 50 years, there has been considerable political progress towards implementing sustainable development processes (Lenschow and Sprungk, 2010; Burns et al., 2020; Lenschow et al., 2020). Historically, one stimulus for these initiatives was the emphasis on environmental protection and sustainable development in The Stockholm Declaration of 1972 (Domorenok and Graziano, 2023), a sentiment echoed in "Limits to Growth" (Meadows and Club of Rome, 1972; Meadows et al., 2004; Best and Meyer, 2022). More recently, proposals for different policy packages and deals have been introduced, which have been fundamental in efforts to preserve ecology and fight climate change (Mastini et al., 2021; Vela Almeida et al., 2023). The most important of these deals are those formed within the European Union, Great Britain, the United States, and Canada, as well as in China, South Korea, and Latin America (Bloomfield and Steward, 2020; MacArthur et al., 2020; Chen and Li, 2021; Leonard et al., 2021; Yoon, 2021; Caggiano and Landau, 2022; Brown et al., 2023; Vela Almeida et al., 2023). The urgency of change was confirmed in the adoption of the Paris Climate Agreement by a number of countries (Falkner, 2016), which the European Union legislatively transformed into the European Green Deal (Barry and Hoyne, 2021). This is considered to be the first published state-run obligation towards climate neutrality (Vela Almeida et al., 2023).

After the signing of the Paris Agreement in December of 2015 (Nations, 2015), and the drafting of the Sustainable Development Agenda for 2030 in the same year (Osborn et al., 2015), a new growth strategy to transform the EU into a just and prosperous society was initiated. Under the leadership of Ursula Von der Leyen, the newly appointed President of the European Commission, the European Green Deal was introduced to secure climate protection, shift key economic sectors in the EU toward sustainability, and lead the transition to a climate-neutral European Union by 2050 (Knodt and Ringel, 2019; Aszódi et al., 2021; European Commission, 2021; Johnson et al., 2021; Kougias et al., 2021; The European Green Deal -). The European Green Deal prioritizes environmental protection by promoting sustainable practices across industries and agriculture (European Commision, 2021; Keenor et al., 2021; Fayet et al., 2022). With the intention of being an example to global economies, the European Green Deal aims to reduce greenhouse gas emission by 50%, reduce the release of harmful products into the environment, and review whether existing policies are climate-safe or not (Aszodi et al., 2021; Buckley et al., 2021; European Commision, 2021). Together, it is hoped that these goals will enable Europe to reach world-leading levels of environmental protection (Aszodi et al., 2021; European Commision, 2021).

One of the European Green Deal plans is to lead nations in phasing out fossil fuel subsidies, which means that all countries will need to transfer to renewable energy sources (Decision (EU) 2022/591 of the European Parliament and of the Council of 6 April 2022 on a General Union Environment Action Programme to 2030, 2022), which will require fundamental changes in economic, social, and industrial fields. However, this ambition is not without its critics: stakeholders are concerned about whether governance of the clean energy transition will be hard rather than soft (Ringel et al., 2021; Schuelke-Leech, 2021); in addition, although Green Deals worldwide have focused on technologies beneficial to people, some studies argue that there is no concern for the socio-environmental costs of these technologies (Dunlap and Laratte, 2022). Nonetheless, the European Green Deal embodies the commitment of Europe to achieve its climate and environmental objectives through green values (White et al., 2019; Tan et al., 2022), asserting that sustainable economic growth can occur without increasing resource consumption in sectors including industry, agriculture, building renovations, and biodiversity conservation (Bonfante et al., 2020; Robbins, 2020). Energy is one of the most concerning issues as the European Green Deal promotes the transition to clean energy to preserve nature and biodiversity for the future (Krämer, 2020). Specifically, the European Union power scheme is grounded in direct electrification and the development of clean energy using fuels such as hydrogen (Fleming and Mauger, 2021). Although financial security is a crucial variable influencing the success of the scheme (Siddi, 2020), the authors state that the Green Deal program is well supported financially. Indeed, they propose mechanisms that would lead to a significant redistribution of public funds into renewable energy efficiency, including subsidies, grants, and incentives (Siddi, 2020; Fleming and Mauger, 2021; Sikora, 2021).

A long-term perspective is key in mitigating climate change (Sikora, 2021), and the European Green Deal is an promising project in this respect. However, to be successful, it needs to be rooted in the constitutional structure of the European Union legal order, particularly solidarity, sustainable development, and advanced safeguarding of the environment (Sikora, 2021). The European Committee unveiled an integrated industrial policy as part of its objective in 2010, and in March 2020, it introduced an industrial strategy that aims to incentivize environmental goals, revitalize regions, and develop cutting-edge knowledge (European Commision, 2010). By lowering carbon emissions by 55% by 2030 and reaching carbon neutrality by 2050, the European Green Deal aims to accelerate the transformation of the European Union into a climate-neutral economy (Sikora, 2021), and to take the initiative in combating climate change on a worldwide scale (Rodríguez-Espinosa et al., 2021). Some of these goals focus on achieving climate neutrality within industry, fostering a green and digital economy, and decarbonizing and modernizing both food and agricultural industries (Ringel et al., 2021; Fayet et al., 2022). The European Union aims to overcome the high energy consumption and low labor force currently evident in agriculture (Robbins, 2020; Rep, 2021); this will require support for farmers, which may be challenging (Rep, 2021). Another emerging policy is focused on waste management and recycling, where the European Union plans to integrate waste registry systems within its countries (Bobba et al., 2020; Sileryte et al., 2022). In line with this, the European Union plans to discontinue outsourcing unused materials externally, and to re-examine its policies around illegal exports and waste shipping (European Commision, 2020).

As mentioned above, society faces a significant challenge in climate change. In the last 50 years, the global conversation on climate change, global warming, and sustainability has also grown (Lipschultz, 2017;

Sabherwal and Kácha, 2021), which evokes certain emotions, feelings, and reactions in individuals (Hayes et al., 2018; Stanley et al., 2021; Pihkala, 2022; Tran and Matsui, 2023). Likewise, issues related to the Green Deal and whether it will fulfil its aim of sustainable transformation are of concern to all stakeholders affected by the deal (Ossewaarde and Ossewaarde-Lowtoo, 2020; Eckert and Kovalevska, 2021; Fleming and Mauger, 2021; Ringel et al., 2021; Samper et al., 2021; Schuelke-Leech, 2021; Hereu-Morales et al., 2023). Finally, climate change itself raises moral and ethical questions for society (Antadze, 2020; Pihkala, 2022), as well as possible fears and negative emotions (Clayton and Karazsia, 2020; Pihkala, 2020; 2022; Ojala et al., 2021). Therefore, along with political and economic perspectives, societal views on climate change and mitigation strategies are key in evaluating the Green Deal.

1.1 The aim of the research and analytical framework

The aim of this research was to uncover public discourse and concerns worldwide through analysis of communication about the Green Deal on the social network Twitter, currently X (in the following text, only the original name Twitter is used, as the data for analysis was downloaded before the renaming of this network; see part 2, Material and methods). As confirmed by numerous studies, social media is broadly used to understand the degree to which people act as individuals or a group (Song et al., 2017; Adzawla et al., 2019; Etemadi et al., 2022; Prieto Santamaría et al., 2022). Social media gives the ideal space for studying this due to the large amount of data generated by millions of people sharing their opinions every day (Sahayak et al., 2015; Pearce et al., 2019): these data are available not only for industrial, but also academic, purposes (Kvasničková Stanislavská et al., 2023; Rosenberg et al., 2023). Within the past decade, since the establishment of the Twitter social network in 2006, more than 27,000 studies including the word Twitter have been published (Antonakaki et al., 2021). Twitter has become a legitimate research platform providing a large quantity of real-time data. These data provide insight into people's opinions on various issues (Gaytan Camarillo et al., 2021; Hussain et al., 2021; Prieto Santamaría et al., 2022), the possibility to analyze tweet sentiment (Ballestar et al., 2020; Vargas et al., 2021; Hassan et al., 2022; Park et al., 2022), and the ability to identify trends in communication (Tran and Matsui, 2023). According to published statistics, the Twitter social platform had 368 million active users per month worldwide, as of December 2022 (X/Twitter: number of users worldwide 2024, 2024). Particularly, Twitter offers a helpful resource for examining public discourse on climate change and the global environment (Pearce et al., 2014; Fownes et al., 2018; Pilař et al., 2019; Effrosynidis et al., 2022; Yao et al., 2022).

Current literature suggests that analyzing the public perception of climate change policies such as the Green Deal may highlight key concerns of the general public. Public opinion therefore plays an important role in influencing the implementation of measures aimed at mitigating and adapting to the effects of climate change (Taufek et al., 2021; Pueyo-Ros and Garau, 2023). Thus, the goal of this research was to obtain a deeper understanding of the Green Deal discourse on social media and to identify sentiment related to particular themes within this space using Twitter analytic techniques. To achieve this research aim, we addressed the following research questions.

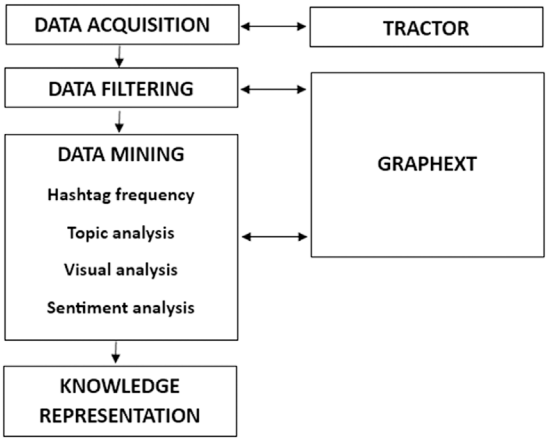


FIGURE 1
The four steps of social media analysis based on the SMAHR framework.

1) What are the most frequently used hashtags in tweets related to the Green Deal?
2) What topics resonate most in discussions (tweets) around the Green Deal?
3) What sentiments are expressed within Green Deal topics discussed on Twitter?

This article offers comprehensive insights into Green Deal communication on Twitter worldwide using social media data analysis techniques. This article contributes to the literature in several ways: it broadens existing knowledge by identifying the leading topics communicated on Twitter; it identifies the type and level of sentiment around the communicated topics; and it identifies the context in which individual topics appear and the sentiment associated with them.

In the following sections, the methodology is described, and the social media context of the Green Deal is discussed, including through content analysis and discourse monitoring.

2 Materials and methods

The data were analyzed based on the SMAHR (Social Media Analysis based on Hashtag Research) framework (Pilař et al., 2021b), which has previously been used to study various topics that resonated on social networks (Pilař et al., 2019; 2021c; 2021a; Šímová et al., 2021; Pilařová et al., 2022; Ježková Petrů et al., 2023; 2023; Kvasničková Stanislavská et al., 2023; Šálková et al., 2023). In the case of this research, the analysis consisted of four steps outlined in Figure 1 and described below.

2.1 Data acquisition

This step aimed to collect data on the Green Deal from the Twitter social network. For this purpose, all messages (tweets) containing the phrase "green deal", the word "greendeal", or the hashtag "#greendeal" were considered relevant. The Twitter API v2

(Twitter, 2015) was used for the extraction of tweets from the Twitter database. TRACTOR software (Graphext, 2023) was set to capture all tweets including ["greendeal" OR "green deal" OR "#greendeal"]. All relevant tweets from 1 January 2019 (the year of the official presentation of the European Green Deal) to 31 March 2023 were retrieved, which comprised 192,567 tweets from 89,328 unique users.

2.2 Data filtering

The data filtration phase aimed to safeguard the dataset's integrity and relevance. This was done by identifying any deceptive content or spam to preserve the dataset's accuracy and dependability. To do this, we thoroughly filtered the dataset, including manual examination, to carefully analyze the dataset. This procedure involved the following steps.

- Filtering messages not containing the keywords "greendeal" OR "green deal" OR "#greendeal", thus verifying that the relevant data had been correctly downloaded.
- Creating a list of Twitter users and the number of tweets created per year, making it possible to detect spam accounts, such as those that promote their products on various platforms. For example, the "Bouncedeals" account posted 1,113 tweets of products it called "green deals."
- Sorting messages alphabetically, making it possible to visually detect whether a certain tweet is being widely distributed among users on Twitter, which could artificially create a separate topic. No such message was found in this case.

Despite the comprehensive nature of our search, we found no misleading messages or spam in the collected tweets. This finding corroborated the high standard of the data and its compatibility for the next stages of the analytical process.

2.3 Data mining

The aim of this step was to extract relevant information from the downloaded dataset. For this purpose, the following analyses were performed.

a. Hashtag frequency. Hashtags have two primary functions on social media: 1) they serve as identifiers of certain topics with which the users associate (mark) their messages (Chang and Iyer, 2012; Pilař et al., 2017); and 2) they are used to emphasize values, experiences, attitudes, and opinions in tweets (Pilař et al., 2017; Childers et al., 2019; Zhang K. et al., 2020). Hashtags were extracted from the dataset (all tweets) by Hashtag extractor software (Pilař et al., 2021a). The calculation of the frequency of individual hashtags was performed by importing the data into Gephi 0.9.2 software (Bastian et al., 2009).

b. Topic analysis. Topic analysis is used to identify the main topics or themes being communicated within a large dataset, such as social media posts. In complex networks, such as social media networks, some nodes (i.e., hashtags or words) are more interconnected with each other than with the rest of the network. This makes it possible to identify topics based on clusters of individual hashtags and words. This part of the analysis aimed to identify the topic structure of discussions related to the Green Deal on Twitter. In comparison to frequency analysis, topic analysis was created based on whole tweets (not only on hashtags). This tool allows better understanding of the dynamics of communication by identifying links between individual hashtags. For topic analysis, Graphext software was used (Graphext, 2020). To analyze the network's community structure, Graphext utilized a modified version of the Louvain algorithm (Blondel et al., 2008). The network was created based on the interconnectedness of individual words in a tweet. The Louvain algorithm employs an iterative process of allocating nodes to clusters with the aim of optimizing a performance metric known as modularity. This metric gauges the relative density of edges within clusters compared with those between clusters. The number of distinct communities in the dataset was calculated as follows:

$$\Delta Q = \left[\frac{\sum_{in} + 2k_{i,in}}{2m} - \left(\frac{\sum_{tot} + k_i}{2m}\right)^2\right] - \left[\frac{\sum_{in}}{2m} - \left(\frac{\sum_{tot}}{2m}\right)^2\right]$$

where $\sum_{in}$ is the sum of weighted links inside the community, $\sum_{tot}$ is the total number of weighted connections inside the community, k_i is the total number of weighted links related to community hashtags, $k_{i,in}$ is the total weighted linkages from an individual to community hashtags, and m is the normalization factor, calculated as the total weighted links over the entire graph (Blondel et al., 2008).

c. Visual analysis. Network visualization techniques such as force-directed layouts can be used to highlight different aspects of a network, such as the density of connections or polarization of topics. The aim of this part of the analysis was to identify the polarity of identified topics. Visual analysis was created using Graphext software (Graphext, 2020). Based on the ForceAtlas layout technique, a two-dimensional graph was generated; specifically, an improved version of the ForceAtlas algorithm, called ForceAtlas2, which focuses on massive networks, was used. This approach uses visual representations of smaller samples to identify network communities' intercommunity connections (Jacomy et al., 2014).

d. Sentiment analysis. Sentiment analysis is used to identify the emotions expressed in tweets about a particular topic (Shamoi et al., 2022). It allows a text to be categorized into positive, negative, or neutral sentiments based on the context and tone of the language used. Sentiment analysis was used to better understand the social atmosphere related to the Green Deal. This method analyzes people's emotions, attitudes, evaluations, and opinions communicated through unfiltered social network posts (Elbagir and Yang, 2019; Eom et al., 2022). For sentiment analysis, we used VADER (Valence Aware Dictionary and Sentiment Reasoner), a Lexicon and Rule-Based Sentiment Analysis Tool (Hutto and Gilbert, 2014; Hota et al., 2021). This part of the analysis aimed to

TABLE 1 The 40 most frequently used hashtags related to the Green Deal on Twitter sorted by frequency.

No.	Hashtag	Frequency	No.	Hashtag	Frequency
1	#greendeal	52,740	21	#energytransition	778
2	#EU	5,865	22	#klimaschutz	778
3	#eugreendeal	3,450	23	#hydrogen	762
4	#climatechange	2,978	24	#co2	756
5	#covid19	1,970	25	#climateemergency	743
6	#sustainability	1,955	26	#innovation	723
7	#europe	1,753	27	#europeanunion	705
8	#climate	1,676	28	#farmtofork	635
9	#energy	1,567	29	#sustainable	623
10	#climatestrike	1,479	30	#renewables	620
11	#green	1,396	31	#energiewende	609
12	#climateaction	1,317	32	#gas	605
13	#circulareconomy	1,207	33	#renewableenergy	599
14	#greennewdeal	1,153	34	#coronavirus	595
15	#europa	976	35	#solar	587
16	#ue	966	36	#h2020	569
17	#fitfor55	950	37	#fossilfuels	535
18	#climatecrisis	905	38	#climat	529
19	#greenrecovery	877	39	#cop26	528
20	#environment	801	40	#timmermans	525

identify sentiments expressed in identified topics related to the Green Deal on Twitter.

2.4 Knowledge representation

Knowledge representation is a critical step in the data analysis process that allows the transformation of raw data and outcomes from previous analyses into intelligible and interpretable forms. This process involves the use of visualization tools and methods that facilitate the communication of complex information and findings to a broader audience. The aim is to provide a clear and concise picture of the insights gained to enable efficient dissemination of all findings and allow important findings to be highlighted (Pilař et al., 2021b).

Within our methodology for knowledge representation, we employed a combination of sentiment analysis, hashtag frequency analysis, and visual analysis of identified themes to provide a comprehensive overview of the dynamics and emotional tone of the discussion on the Green Deal on Twitter. Sentiment analysis enables identification and categorization of the emotions expressed in tweets, thus offering a deeper insight into public sentiment, whether positive, negative, or neutral, and uncovers areas of broad support or controversy. Hashtag frequency analysis reveals which key terms, hashtags, or themes dominate the conversation, aiding in the identification of the most heated topics of discussion. Visual analysis focuses on the polarity of individual themes, utilizing advanced visualization techniques for interpreting and displaying this polarity through intuitively understandable maps. This approach offers unique insight into the complex structure of conversations about the Green Deal and reveals how themes are interconnected.

3 Results and discussion

3.1 Hashtag analysis

There were 192,567 tweets from 89,328 unique users with Green Deal content as explained in the Methods section above. Table 1 shows the top 40 most frequently used hashtags associated with Green Deal Twitter conversation. The hashtag with the highest frequency was "#greendeal," one of the search conditions in the Python script used when downloading the data. The high frequency of this hashtag (52,740) confirms its utility as a marker of messages on the Green Deal.

The second most frequently used hashtag 2) was "#EU," by which many users underline that their tweets are related to the European Green Deal. This emphasis was also evident in the third-most frequent hashtag, "#eugreendeal" 3) and the synonymous "#europeanunion" (27) and "#UE" (16), which continued to appear in the analyzed tweets, including in those with language

mutations. Language mutations appeared mainly in French, Italian, or Spanish, e.g., "#europe" 7) and "#europa" (15). The worldwide debate on the Green Deal often combines all proposals under a single Green New Deal, especially in G20 countries (Lee et al., 2021; Mogos et al., 2023). Therefore, in debate specifically concerning the European policy framework, academics, professionals, and the public use "European Green Deal" (Mastini et al., 2021; Rosamond and Dupont, 2021; Vela Almeida et al., 2023).

Another group of associated hashtags were those connected with climate change because users often point to the importance of the Green Deal in solving this issue. Examples of these hashtags include "#climatechange" 4), "#climate" 8), "#climatestrike" (10), "#climateaction" (12), "#climatecrisis" (18), "#klimaschutz" (22; climate protection in German), "#climateemergency" (25), and "#climat" (38). That "#climatechange" was in fourth place suggests that climate change is strongly associated with the Green Deal and its aim to mitigate the consequences of climate change (Melidis and Russel, 2020; Barry and Hoyne, 2021; Sikora, 2021; Carter and Pearson, 2022; Cifuentes-Faura, 2022). This association is particularly pertinent given the current consequences of climate change in Europe (Clayton et al., 2015; Hrabok et al., 2020; Pihkala, 2020).

The popularity of the hashtags "#covid19" 5) and "#coronavirus" (34) suggest that the COVID-19 pandemic raised discussion about to what extent the pandemic might impact the European Green Deal or Green New Deals and their implementation (Dupont et al., 2020; Gosens and Jotzo, 2020; Crnčec, 2021; Cassetti et al., 2023). In fact, studies confirm that the reaction of the European Union to COVID-19 strengthened the need to implement the European Green Deal (Sovacool et al., 2020; Crnčec, 2021; Smol, 2022). Indeed, previous research shows that areas with higher levels of air pollution suffered the hardest after-effects of COVID-19 (Bashir et al., 2020); therefore, implementation of green environmental policies may reduce the spread of infectious diseases and their impact in the future (Bashir et al., 2020; Becchetti et al., 2021).

The hashtags "#sustainability" 6), "#green" (11), "#circulareconomy" (13), "#environment" (20), "#sustainable" (30), and "#renewables" (21) were included within discourse on sustainability. Discussion about sustainability in the environmental and social sciences does not often correlate with, and in fact often contradicts, politically motivated discourse, which widens the debate over the European Union's sustainability ambitions (Eckert and Kovalevska, 2021). Although there are industries where practitioners are reluctant to adopt circular economy practices (Bonoli et al., 2021), use of the "#circulareconomy" hashtag suggests discourse is rising around the need to transition from a linear economy, with stakeholder support increasing through sharing changes in their own social and personal behavior (Van Buren et al., 2016).

One aspect of sustainability is sustainable energy sources, which are enforced by the Green Deal. Discussion around this topic included the hashtags "#energy" 9), "#energytransition" (21), "#hydrogen" (23), "#energiewende" (31; energy transition in German), "#renewableenergy" (33), and "#solar" (35). However, some tweets also addressed the other side of this issue, including carbon dioxide production ("#co2", 24), and the burning of fossil fuels ("#gas", 32 and "#fossilfuels", 37). The majority of the debate corresponded to the energy transition, with renewable energy predicted to make up the majority of the world's energy profile by 2050 (Jianhua, 2022); however, the perception of renewable energy development differs from acceptance to refusal, depending on the country (Pellizzone et al., 2017; Oluoch et al., 2022; Spampatti et al., 2022; Tidwell and Tidwell, 2022; Panarello and Gatto, 2023).

A separate group of tweets included those that mark other policies (or political events) with which the Green Deal is related, such as "#fitfor55" (17), "#farmtofork" (28), "#H2020" (36), and "#COP26" (39). The European Union's Fit for 55 package is an unparalleled set of policies and tools that by 2030 aim to reduce greenhouse gas emissions by 55% compared with 1990, and by 2050 aim to achieve net zero emissions (European Commision, 2021; Ovaere and Proost, 2022). The farm to fork strategy is a fundamental part of the European Green Deal. It focuses on a sustainable transition in agriculture, sustainable food value chains, food security, and sustainable nutrient management (European Commission, 2021). However, stakeholders have polarized attitudes towards the farm to fork strategy, as reported in previous studies (Zhang A. et al., 2020; Alsetoohy et al., 2021; Georgescu et al., 2022; Adina et al., 2023; Aerni, 2023). The hashtag "#H2020" represents Horizon 2020, the European Union's €80 billion research and innovation funding program contained within the Innovation Union strategy, which ended in 2020 (European Commission, 2020); Horizon 2020 succeeded the European Commission for Research's previous framework (Veugelers et al., 2015). The last hashtag from this group, "#COP26," refers to the 26th climate change conference, the so-called Conference of Parties (COP) 26, which led to commitments ensuring sustainable economic progress towards the goals outlined in the Paris Agreement, as well as agreement on pledges to curtail climate change (Bai et al., 2023).

Finally, from the list of the most used hashtags, three remain that were not directly classifiable into any previously mentioned group. The hashtag "#greennewdeal" (14) refers to the topic of the Green New Deal, which is the United States equivalent of the European Green Deal (Boyle et al., 2021); the hashtag "#innovation" (26), which is related to the search for green innovations required to meet the commitments of the Green Deal, and to the Horizon 2020 funding program (Veugelers et al., 2015; Aydin et al., 2023; Otto et al., 2023); and the hashtag "#timmermans" (40), which refers to the former vice-president of the European Commission, Frans Timmermans, who was responsible for the realization of the Green Deal in the European Union.

3.2 Topic analysis with visual and sentiment analysis

Topic analysis allows a better understanding of the dynamics of Twitter communication by identifying links between individual components of tweets (hashtags, words, and phrases). The results of the topic analysis are shown in Table 2. This table includes 16 topics that contained 1,000 or more tweets. The topics are sorted according to the absolute and relative (%) frequency of tweets that fall within the given topic; together, these topics cover 89.39% (172,135) of the downloaded tweets. Further visual analysis in Figure 2 aimed to identify the interconnectedness and/or

TABLE 2 Identified topics related to "#greendeal" on Twitter.

No.	Topic	Frequency of the topic		Key terms
		%	No.	
1	European Green Deal	38.66	74,448	EU, Europe, European Green Deal, European Commission, von der Leyen, policy, climate, climate change, plan, energy, sustainability, transition, innovation, 2030, 2050
2	Green New Deal–Political perspective	18.95	36,483	New Green Deal, America, people, want, need, vote, government, democrats, socialist, Alexandria Ocasio-Cortez (AOC), Trump, money, work, job, tax, oil, bill
3	Green New Deal–Environmental perspective	8.33	16,042	New Green Deal, climate change, renewable, crisis, environment, planet, world, global, time, need, want, carbon, CO2, emission, energy, power, electric, fossil, gas, fuel, coal, wind, solar
4	War in Ukraine	4.00	7,704	EU, Ukraine, Russia, Putin, war, energy, fossil-fuel, gas, oil, coal, industry, ECT (Energy Charter Treaty), nuclear treaty, noECT, block bold climate action, dangerous treaty, stop climate-killer treaty, neutrality if the energy
5	Farm to fork	2.88	5,554	EU, European Green Deal, farm to fork, food, agriculture, strategy, policy, CAP (Common Agricultural Policy), sustainable, commission, production, biodiversity, pesticide
6	European Commission representatives	2.68	5,155	Frans Timmermans, EU, Ursula von der Leyen, cartoon
7	Transport	2.02	3,895	EU, European Green Deal, sustainable mobility, travel, electric, clean, reduce, emission, CO2, 2050, 2035, target, achieve, goal, rail, aviation, car, air, maritime
8	Alexandria Ocasio-Cortez (AOC)	1.58	3,045	New Green Deal, AOC, Cortez Alexandria-Ocasio, Kamala Harris, Tammy Bruce, Nancy Pelosi, dems promoting, socialist, work quilt, new green hoax, promoting a fraud, moronic new green deal, quilt promising a cure
9	Joe Biden	1.56	2,999	New Green Deal, American, Joe Biden, Biden's Green Deal, Trump, Harris, Bernie Sanders, want, support, people, vote, gas, oil, taxis, prices, high, job, destroy, lie, China
10	Industrial plan	1.54	2,971	Industrial plan, Green Deal Industrial plan, 2050, Europe, neutral continent, European Commission
11	Italian perspective	1.33	2,556	Italy (Italia); deal for Italy (deal per l'italia), green deal europeo (European Green Deal), continente neutro (neutral continent), project (progetto), challenge (sfida), marathon (maratona), environment (ambiente), transition (transizione), opportunity (opportunità), sustainability (sostenibilità), renewable (rinnovabile), development (sviluppo), economy (economia), business (impresa), agriculture (agricoltura), emerge from the pandemic (pandemic uscire dalla pandemia), pandemic (pandemia)
12	Dutch perspective	1.28	2,461	Green Deal, concern (zorg), sustainability (duurzaamhei), farm to fork, agriculture (landbouw), farmer (boer), education (onderwijs), nature-inclusive agriculture (natuurinclusieve landbouw)
13	COVID-19	1.13	2,170	Coronavirus, covid-19, pandemic, resilient recover, after covid-19, deal must be central, recovery after covid-19, covid-19 climate home, WeMove.eu
14	Hydrogen	0.96	1,843	Greendeal, Europe, hydrogen, energy, battery, fuelcell, green hydrogen, zero-emission, fuel, renewable energy, electrification, clean energy, lithium, storage, industry, production, company, hydrogen economy
15	Circular economy	0.94	1,818	European Green Deal, circular economy, recycling, circular economy erected, chemicals strategy, reuse, sustainability, action plan, number one priority, adopt, waste, plastic, packaging, material, raw materials, toxic
16	Renewable energy	0.82	1,576	Renewable energy, electricity, power, solar, solar panels, solar for business, wind, free solar, fee exemption, energy efficiency, energy savings, delays but keeps the climate, keeps climate target plan

polarization of individual topics. The results of the sentiment analysis are shown in Figure 3. This analysis sorts the opinions and attitudes expressed by users in tweets into three categories: positive, neutral, or negative sentiments.

GND, Green New Deal; Polit. persp., political perspective; Envi. persp., environmental perspective; EC, European Commission; AOC, Alexandria Ocasio-Cortez. The largest (first-placed) topic (38.66% of tweets) was the "European Green Deal," a set of

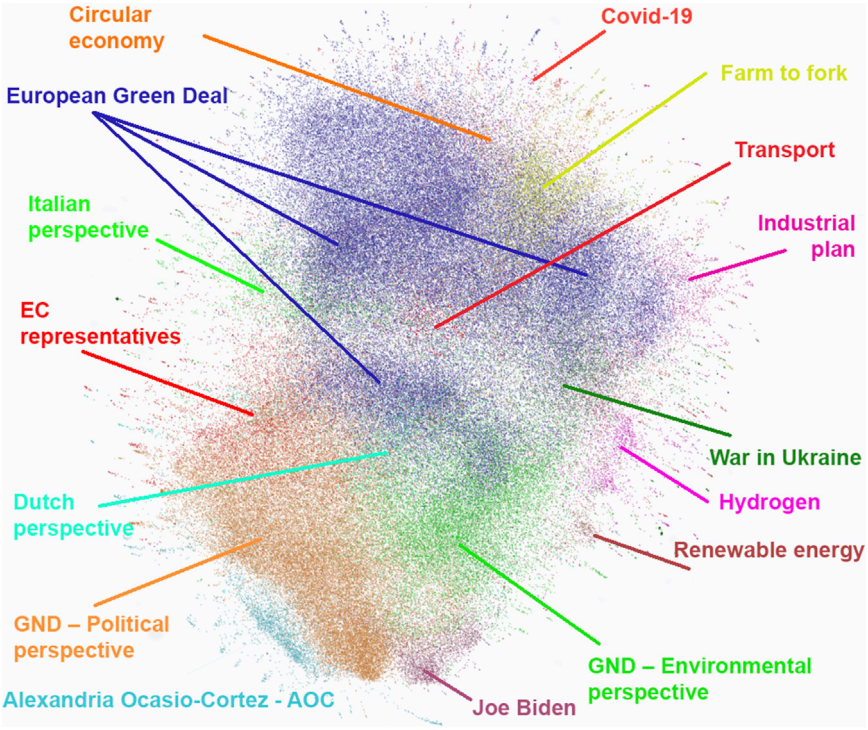


FIGURE 2
Visual analysis of the interconnectedness and polarization of discussion related to the Green Deal on Twitter.

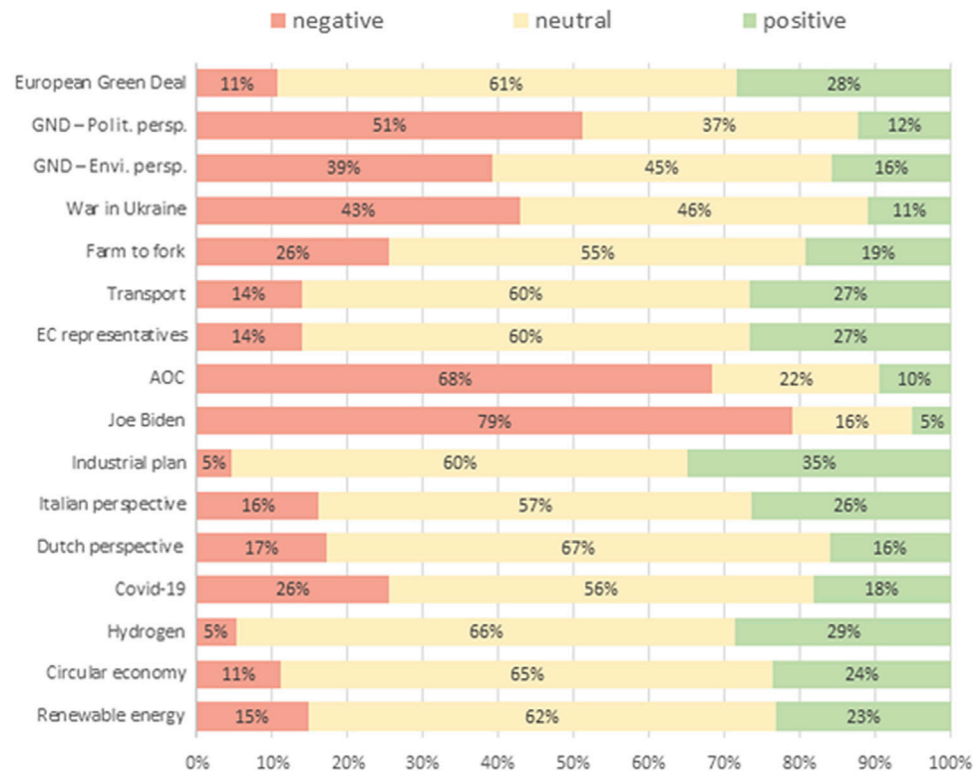


FIGURE 3
The proportion of negative, neutral, or positive sentiments associated with the identified topics.

proposals that put the European Union on track to achieve its 2030 climate goals in a fair, cost-effective, and competitive way (European Commision, 2019). The discussion was usually around climate change, sustainability issues, the necessity of an energy transition, innovations, and plans and policies. Although public perceptions of climate change are frequently incomplete, incorrect, and heavily affected by the media, it is crucial to engage the public in addressing this issue, as their behavior plays a crucial role in both creating and reacting to global climate change (Clayton et al., 2015; Rousell and Cutter-Mackenzie-Knowles, 2020). The name of the main bearer of the European Green Deal proposal was also often mentioned in the topic, for example, the "European Commission," as well as its chairwoman and proponent (Ursula) "von der Leyen" (Domorenok and Graziano, 2023; Vela Almeida et al., 2023). Figure 2 shows polarization between the "European Green Deal" topic (dark blue in Figure 2) and the four topics related to the United States Green New Deal ("GND–Political perspective," "GND–Environmental perspective," "AOC," and "Joe Biden"). By contrast, the "European Green Deal" was closely connected with discussion of other green topics within the European Union. The "European Green Deal" was the third-highest topic where positive sentiment prevailed over negative (28% positive, 61% neutral, and 11% negative). High levels of neutral and positive emotions were linked to keywords relating to the European Commission, its policies, and the content of individual European Green Trade documents (Ringel et al., 2021; Borghesi et al., 2022; Garito et al., 2023). In general, moods associated with European topics were moderate (neutral), and in some case, positive reactions even prevailed over negative ones.

A large part of the discussion was devoted to the Green New Deal (GND), particularly the Green New Deal of the United States. However, it was divided between several separate topics, which included political arguments (no. 2, "GND–Political perspective") and conversations surrounding its most significant protagonists (no. 8, "Alexandria Ocasio-Cortez" and no. 9, "Joe Biden"). In all the topics mentioned, negative sentiment significantly prevailed, mainly in the politically oriented discussions. Fifty-one percent of tweets had a negative sentiment, 37% were neutral, and 12% were positive. Expressions such as "democrats" and "socialist" appeared regarding this topic, whose differing views on the Green New Deal are discussed in other studies (Galvin and Healy, 2020; Ajl, 2021; Boyte and Throntveit, 2022). As the content of the Green New Deal is focused on changing to a sustainable economy, related discussions regarding elections, government, and taxation (Dogan et al., 2023), as well as the American society, jobs, and the workforce, were also present (Lachmann, 2022).

The environmental side of the Green New Deal (no. 3, "GND–Environmental perspective") seemed to be in the background of these topics. The environmental perspective of the Green New Deal partially overlapped with the "European Green Deal" topic, suggesting that the discussion at the core of these environmental agreements are similar. These include debates over the deployment of state power to gradually decarbonize economies, revitalize communities, and limit emissions (Green, 2022; Driesen and Mehling, 2023). Other key terms used within this topic were words like "climate change," "planet," "world," "global," and "environment," as well as terms related to energy resources like "renewable," "fossil," "energy," "power," "electric," "gas," "coal," "wind," and "solar" (Bagus and Peña-Ramos, 2023; Belaïd et al., 2023; Donaghy et al., 2023). Previous studies suggest that the transition of economies towards sustainability provokes discussion from those who see the changes on which the Green New Deal is based as necessary. The methods of change, especially renewable resources and energy acquisition, are also at the center of debates, not only among the public, but also political critics (Bloomfield and Steward, 2020; Allam et al., 2022; Lachmann, 2022) and academics (Pilař et al., 2019; Green, 2022; Chaudhuri and Huaccha, 2023; Morgan et al., 2023; Presberger and Bernauer, 2023). Although the debates were associated with criticism, there was not such a negative sentiment compared with the political perspective of the Green New Deal: the rate of negative posts was 39%, with neutral and positive posts accounting for 45% and 16%, respectively.

The fourth-most discussed topic was "War in Ukraine" and discussion of the possible consequences of this geopolitical conflict (Sandri et al., 2023; Siddi, 2023), especially in connection with the "European Green Deal," "Transport," and "Hydrogen," which is evident in the visual analysis in Figure 2. The mood of tweets was largely negative (43%) or neutral (46%), with a positive sentiment of only 11%. Previous research supports these findings and the discourse around individual topics related to the war in Ukraine, as the potential consequences on energy supplies, fossil fuels, and industry, are discussed (Farrell and Newman, 2019; Goldthau and Sitter, 2022; Ciot, 2023; Rečka et al., 2023; Romanova, 2023; Sheth and Uslay, 2023). In response to the war in Ukraine, the European Union reformulated policies to enforce interdependence on gas suppliers through diversification of fuels and clean energy, including renewable resources such as hydrogen, wind, and solar (Kalantzakos et al., 2023; Kaldor, 2023; Proedrou, 2023).

The discussion topic "Farm to Fork" was the fifth-largest topic; sentiment was neutral (55%) to negative (26%), with 19% positive tweets. This topic was polarized from other sub-policies, such as "Hydrogen" and "Renewable energy," and had the highest proportion of negative emotions out of the topics related to European Commission policies. As confirmed by previous studies, negative or questioning perceptions exist among farmers, especially regarding the increasing costs, decreasing income, and reduced profitability associated with farm-to-fork initiatives (Riccaboni et al., 2021; Cortignani et al., 2022; Adina et al., 2023). This topic was associated with the terms "EU," "European Green Deal," "food," "agriculture," "strategy," "policy," "Common Agricultural Policy," "biodiversity," and "pesticide" (Borrelli et al., 2023; Lecina-Diaz et al., 2023; Rudnicki et al., 2023). From the results, it was evident that the "Farm to Fork" topic was also discussed at the regional level, as shown by its inclusion as a key term within the 12th topic, the Dutch perspective.

Topic number six, "European Commission representatives," dealt with content in which representatives were the target of cartoon caricatures. These were aimed at both main representatives of the European Green Deal, Ursula von der Leyen and Frans Timmermans, and were also associated with the words "EU" and "cartoon." This topic was polarized from topics about Alexandria Ocasio-Cortez and United States President Joe Biden. The results show that this topic was perceived more positively (27%) or neutrally (60%) due to the humorous content included in these tweets. Caricatures are usually hand-drawn pictures or

cartoons that express ideas, themes, and situations that would be complicated to describe through text, and political cartoons and caricatures are increasingly framing europolitical topics in media (Van Hecke, 2017). These images contain overstatements and sarcasm aimed to inform and amuse, as well as to publicize information in a funny way (Marín-Arrese, 2008; Swain, 2012; Jaashan, 2019) and represent a powerful tool in communication, with research suggesting that the public more easily accepts messages from caricatures than text (Chalániová, 2011).

The subject of the seventh-most high-ranking topic was "Transport" on the old continent, the shape of which will be significantly changed by the European Green Deal (McNamara, 2023; Oberthür and von Homeyer, 2023). The key terms in this topic were "European Green Deal," "sustainable mobility," especially in terms of urban mobility (Tsavachidis and Petit, 2022), "electric," "emissions," "CO_2," "rail," "aviation," "car," "air," and "maritime" (Benga et al., 2023; Modarress Fathi et al., 2023), as well as the years significant to the policy, "2035" and "2050" (Fleming and Mauger, 2021). Transport was discussed with a largely neutral (60%) or positive mood (27%), rather than a negative mood (14%). The position was closely related to the "European Green Deal" topic and overlapped with the "War in Ukraine" and "Industrial plan" topics. The discussion surrounding transportation issues during the war, including disruptions to rail and road networks, underscores the importance of achieving resource independence from external providers (Kalantzakos et al., 2023; Sheth and Uslay, 2023).

The leading negative tweets were related to the names of United States political representatives (no. 8, "Alexandria Ocasio-Cortez" and no. 9, "Joe Biden"). Both were discussed with high degrees of negativity (68% and 79%, respectively) with visible polarization from most topics, but high interconnectivity with "GND–Political perspective" (topic no. 2). Since 2019, Ocasio-Cortez has been a member of the United States House of Representatives. She is the youngest woman ever to serve in the United States Congress (Andersson et al., 2019) and became known mainly for her pre-election speech, her activist involvement in 2016, and her significant activity on social networks. The last point has previously been discussed in studies focusing on political fandom: Ocasio-Cortez shows the ability to successfully leverage social networks, especially Twitter, to create a fan base (Rasulo, 2020; Santamaria, 2021; Rubio and Conesa, 2022). However, her high levels of activity draw both supportive and negative comments, the latter including satire, ridicule, and sexism and racism (Rodriguez and Goretti, 2022), as well as those from political and publicist opponents including Nancy Pelosi and Tammy Bruce. Discussion of climate change brings criticism from activists promoting fraud and green hoaxes (Strong, 2022); for example, after Joe Biden's administration introduced the Green New Deal, the volume of discussions and criticism rose sharply (Rowe, 2020; Cha et al., 2022), with former president Donald Trump's defenders leading this rhetoric (Kou, 2023). However, this criticism is not necessarily a negative: the Green New Deal aims to tackle fundamental and currently unsolvable environmental problems, and it would be remiss not to consider the issues and the trade-offs that will be required (Olsson and Janssens, 2021; Butterfield and Bullen, 2022).

The greatest degree of positive sentiment was associated with the 10th topic, the "Industrial plan" (35% positive, 60% neutral, and 5% negative). According to research, before the launch of the European Green Deal Industrial Plan (European Commission, 2023), shortcomings were identified in the political package addressing climate change (Pianta and Lucchese, 2020). In relation to this topic, comments appeared clarifying this as part of European Green Deal policy. The visual analysis shows the polarization of this topic from most other topics; however, discussions were interconnected with the "European Green Deal" topic with common terms including "Europe," "European Commission," "neutral continent," and "2050" (Holz et al., 2021; Huo et al., 2023).

According to the titles of topics no. 11 ("Italian Perspective") and no. 12 ("Dutch Perspective"), it is evident that the Green Deal is discussed in the local language in some countries. However, the discussion in Italy was rather varied, and the topic included terms such as "neutral continent," "transition," "sustainability," and "renewable" (Marelli, 2021; Prontera, 2021; Di Pirro et al., 2022). The Green Deal offers targeted incentives for integrated, community-related projects in rural areas (Rangone and Ali, 2021). The sentiment being more neutral (57%) or positive (26%) suggests that Italians see the positive opportunities in the European Green Deal. In the Netherlands, the main subject of the discussion was "agriculture," "Farm to Fork," "farmers," and "nature-inclusive agriculture" (Anderson et al., 2021; Friedmann, 2021; Wesseler, 2022; Wilts Jansen, 2023), with the mood more neutral (67%) and negative (17%). Based on the visual analysis of topics (Figure 2), the "Dutch perspective" appears to draw a border between the discussions in Europe and the United States; indeed, the Dutch sustainable approach has been presented as a global example (Friedmann, 2021).

The smallest topics at the end of Table 2 deal with the topics "COVID-19" (no. 13); energy sources, which are divided between "Hydrogen" (no. 14) and "Renewable energy" (no. 16); and the "Circular economy" (no. 15). The positions of these topics in the visual analysis in Figure 2 suggest that "COVID-19" and "Circular economy" are almost exclusively communicated within European discussions, while "Hydrogen" and "Renewable energy" seem to be related to a similar extent to the "GND–Environmental perspective" topic. The "COVID-19" topic is mostly related to discussion of economic and social recovery after covid and building resilience for the future (Smol, 2022; Cassetti et al., 2023; Ryner, 2023); perceptions around this topic were neutral (56%) and negative (26%). Topic 14, "Hydrogen," had the second-most positive sentiment (29%), although the majority of tweets were neutral (66%). Terms associated with this topic were "fuel," "electrification," "batteries," "energy," "clean energy," "industry," "production," and "hydrogen economy" (Fleming and Mauger, 2021; Kakoulaki et al., 2021; Igliński et al., 2022; Włodarczyk and Kaleja, 2023). "Circular economy" (no. 15) was mostly discussed in neutral (65%) or positive (24%) tones with 11% of tweets having negative sentiments. Connected with this topic were terms such as "circular economy," "recycling," "reuse," "packaging," "waste," "raw materials," "plastic" and "toxic" (Bonoli et al., 2021; Krajnc et al., 2022; Mihai and Ulman, 2023). The smallest topic, "Renewable energy" (no. 16), discussed "renewables," "energy resources," "savings," "efficiency," "solar," and "wind" (Hainsch et al., 2022; Panarello and Gatto, 2023). In this topic, there was a mostly neutral tone (62%), followed by positive (23%) and negative (15%) tones.

Previous studies show that discussion on the topic of climate change is mainly accompanied by negative sentiment and steps

leading to its elimination are generally perceived positively (Cody et al., 2015; Dahal et al., 2019; Taufek et al., 2021), especially when it comes to the necessity of carbon neutrality (Xiang et al., 2021), the transition to renewable energy sources (Loureiro and Alló, 2020), and the idea of a circular economy (Maulida, 2023). Analysis of public opinion is key to understand how people take measures to mitigate the effects of climate change (Taufek et al., 2021; Pueyo-Ros and Garau, 2023). Our results show that positive sentiment slightly prevailed around the "Industrial Plan" (35%), "Hydrogen" (29%), the "European Green Deal" itself (28%), "Transport" (27%), and the "Circular Economy" (24%). This suggests that public acceptance of these policies (or changes in these areas) can be considered somewhat more successful than, for example, "Farm to Fork", where a negative sentiment prevailed (26%).

None of the above topics, however, had such a clear preponderance of negative sentiment as American topics. Above all, negative sentiments were obvious in politically oriented topics: "GND–Political perspective" (51%), "AOC" (58%), and "Joe Biden" (79%). This only confirms previous findings that in the United States, the discussion surrounding solutions to climate change are heavily politicized and much more aggressive (Cody et al., 2015; Dahal et al., 2019). Within European topics, the discussion was much more moderate, as evidenced by the discussions at the local level, particularly the "Italian perspective" and the "Dutch perspective" (positive 26% and 16%, respectively; negative 16% and 17%, respectively). Although more moderate than sentiment in the United States, the differences between these countries indicate that sentiments surrounding climate change and the ways to tackle it may differ between individual European states, findings similar to previous studies (Loureiro and Alló, 2020).

4 Conclusion

In general, the perception of climate change is a controversial topic that has been heavily influenced by media coverage for over 30 years (Clayton et al., 2015; Rousell and Cutter-Mackenzie-Knowles, 2020; 2020; Saari et al., 2021; Hereu-Morales et al., 2023). The topic is often discussed on social media, which nowadays plays a significant role in disseminating information. As there are no borders on social media, it is possible to follow the views of discussants globally. In addition, discussions on social networks provide a certain anonymity, so it can be assumed that participants are expressing genuine opinions in real time. Public discourse on climate change has risen in response to a number of political deals and agreements, such as the Green Deal. Based on our results, we answered predetermined research questions and filled the knowledge gap regarding the public perception of the Green Deal and concerns associated with this policy.

Hashtag analysis results answered the first research question, by revealing the most frequently used hashtags and their level of frequency 1). Analysis of hashtags on Twitter found that "#greendeal" (52,740) was the most frequently used hashtag in the analyzed discussions, followed by "#EU" (3,450) and "#eugreendeal" (3,450). We also found that almost two-fifths of tweets discussed the European Green Deal as a set of proposals to steer the EU towards its 2030 climate goals. Further results answered the two following research questions through identification of the most discussed topics 2) and the sentiment expressed within these topics 3) within Green Deal discussions on Twitter. In total, 16 related topics were identified, each of which contained at least 1,000 tweets; the presence of positive, neutral, or negative sentiments within these tweets varied by topic and location. Negative sentiment prevailed in US-related topics, especially the politically oriented ones, for example, "GND–Political perspective," "AOC," and "Joe Biden." The most significant optimism (positive sentiment) prevailed around the "Industrial Plan," "Hydrogen," the "European Green Deal" itself, "Transport," and "EC representatives." However, in the case of the latter topic, positive sentiment can likely be attributed to the satirical nature of the content. By contrast, a greater negative sentiment was found in two topics, "War in Ukraine" and "COVID-19." Among other European-focused topics, more negative tweets were related to "Farm to Fork". Within the EU, it became apparent that countries had a different opinion of the Green Deal, as demonstrated by the "Italian perspective" and "Dutch perspective": analysis within these topics suggested that Italians perceived Green Deal issues more positively than the Dutch. Our research shows that discussion of the Green Deal elicits both positive and negative public reactions; this suggests careful analysis and understanding of the public's voice is required as society engages with and shapes global environmental efforts.

Given the seriousness of this global challenge, approaches to tackle climate change must be comprehensive, long-term, and global. The thorough analysis of Twitter data related to Green Deal conversations highlights public perceptions and the interconnectedness of different aspects of the Green Deal. We observed a diverse debate marked by different attitudes to different topics and intersectionality revolving around the European Green Deal and its resonance on both a regional and global scale. Policymakers, decision-makers and stakeholders may utilize these insights to interact more effectively with the public on social media platforms and enhance communication strategies. Governments and decision-makers can utilize the findings of this research to assess public support for different policies in theory and action. Identifying emotional responses and opinions influenced by disinformation across social networks could help design tailored interventions to counteract false narratives while promoting public confidence through awareness campaigns.

However, it is critical to recognize certain inherent limitations in our research that should be accounted for in future research. Despite the large amount of data reviewed, we still may not have captured the entire spectrum of opinions and sentiments related to the Green Deal on Twitter. The views of those discussing the issue are diverse and may be influenced by many factors such as geographical location, government policies and actions, the quality and objectivity of the media, generational differences and personal experiences, and knowledge and scientific awareness of the issue. One of the main limitations of our research is that it only analyzed posts on Twitter, which is a specific social network, and users' opinions on other social networks or forums might differ. Another limitation is the use of machine text processing, which, despite high technological sophistication, may not always understand the nuances in tweet sentiment (for example, irony may be misunderstood in sentiment analysis).

Regardless of these limitations, our research offers several future research directions. Conducting comparative analysis across different areas and countries may provide insight into disparities in perspectives and sentiments regarding the Green Deal, providing insights into how global opinions toward environmental policies differ. Longitudinal studies may reveal shifting public sentiment and concerns as the Green Deal conversation evolves in response to policy changes and major events. Future research should delve deeper into the sentiments expressed within the Green Deal discourse, which would entail going beyond automated sentiment analysis and using qualitative research methods to gain a better understanding of the motivations and justifications for positive and negative opinions. Furthermore, user profiling may assist in identifying key stakeholders and influential voices within the conversation, allowing for a more granular understanding of the dynamics at work, while integrating further social network analysis with the data collected from Twitter may reveal significant opinion leaders and information circulation trends within the Green Deal conversation. Such an approach could shed light on how opinions spread and key nodes in the conversation's network structure. Including a broader range of social media platforms, reports, and media outlets in the analysis would also provide a broader perspective on public discourse and coverage through the media. Finally, future research could look into the actual impact of the Green Deal and similar policies on environmental and economic outcomes, allowing assessment of the efficacy of such policy initiatives; this would help to bridge the gap between policy intent and real-world consequences, providing valuable insights into the effectiveness of environmental policies.

In conclusion, our research contributes to a greater understanding of the Green Deal discourse on Twitter; however, it also emphasizes the need for further scientific investigation. In future, research should build on these findings by gaining a better understanding of public sentiment, policy implications, and the complex factors influencing environmental debates in the digital era.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by CULS Ethics Committee - This grant is funded via FEM grant, where is the purpose of the research is also assessed from an ethical point of view.

Author contributions

TB: Conceptualization, Formal Analysis, Writing–original draft, Project administration. LuP: Formal Analysis, Resources, Writing–original draft. MP: Data curation, Investigation, Validation, Visualization, Writing–original draft. MJ: Resources, Writing–original draft. LS: Formal Analysis, Resources, Writing–original draft. LaP: Conceptualization, Formal Analysis, Funding acquisition, Methodology, Supervision, Writing–original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Green finance and the silver economy: catalyzing China's low-carbon development

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KEYWORDS

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1 Introduction: China's emerging silver economy

As global population ageing accelerates (Harper, 2014), the Anthropocene is increasingly becoming a world dominated by older adults. Addressing the nuanced needs of various age groups becomes crucial in understanding the intricate link between human activities and environmental shifts (Lindsey et al., 2022). China's adoption of the silver economy emerges as a pivotal response to ageing challenges, as the same time China also has the need for low-carbon transformation of social-economic development. Therefore, China's silver economy can present an opportunity for green finance committed to low-carbon transformation. This opinion article builds upon an understanding of green finance and the silver economy's concepts and scopes, discussing how the changing needs and preferences of older adults affect the transformation of green consumer behaviour and purchasing habits within the silver economy. We summarized the potential and feasibility for targeted green finance to engage with the silver economy, and offered strategies at the green-product, household, and community levels. We point that green finance as a crucial driver for the ecological transformation of the silver economy, promoting innovation and providing greener options for an ageing society.

Human activities are disturbing the Earth's natural cycles, propelling it into the Anthropocene with more uncertainty (Steffen et al., 2011; Steffen et al., 2018). This era is characterized by urbanization and globalization, highlights two significant challenges, climate change and ecological crisis. In this context, social equity becomes crucial, particularly in protecting marginalised groups from climate adversities (Heyd, 2021). The era also underscores the need for integrated approaches that combine climate action with economic growth and human wellbeing (Pincetl, 2017; Angeler et al., 2020; Cork et al., 2023). While the 'Silvering Anthropocene' describe a new phase where increased ageing demographic intensifies challenges for sustainable development. According to the UN, the global population aged 65 and above is expected to grow from 10% in 2022 to 16% by 2050 (Gerland et al., 2022), impacting labour, industry, and consumer patterns, and highlighting ageing's potential to drive economic opportunities (Laperche et al., 2019). The silver economy, which includes public and consumer spending related to ageing, and industrial opportunities aimed to older adults (Lipp and Peine, 2022), reframes concerns around rising healthcare and pension costs, and a shrinking workforce and tax base, by highlighting the economic opportunities of this demographic shift. China, the largest developing economy, the rapidly ageing population is seen as vital to future consumption-oriented economy (Smith et al., 2014; Feng et al., 2020; Han et al., 2020; Xu and Liu, 2023). At the first China State Council executive meeting of 2024, China's government prioritized

the silver economy to a key part of the national socio-economic strategy (CGTN, 2024), recognising its potential to fuel growth across various sectors.

To align the goals set at the 20th National Congress of the CPC, promoting a green ecology and harmonious human-nature coexistence becomes paramount (Xue et al., 2023). Within the framework of whole nationwide climate action and pursuit of a green lifestyle, integrating the silver economy with low-carbon innovation emerges as a key sustainable development strategy in the Silvering Anthropocene. This approach not only addresses the needs and potential of an ageing population but also meets with China's broader environmental goals.

2 Convergence of the silver economy and green finance: exploring possibilities and feasibility

Green finance is recognized as an approach to mitigate the negative environmental effects of human actions since the Industrial Revolution, it underscores the importance of harmonizing economic progress with environmental conservation (Vitousek, 1994; Steffen et al., 2011; Udeagha and Ngepah, 2023). Developed nations, especially the European Union with its pioneering carbon emissions trading, have led green finance initiatives (Berrou et al., 2019; Zhang, 2023). In recent years, China has acknowledged green finance's role in sustainable development and launched initiatives supporting environmental improvement and efficient resource use (Hu J. et al., 2021; Lv et al., 2021; Gu et al., 2023). Green finance transcends being merely an economic instrument; it signifies China's dedication to embedding environmental awareness within its financial and development policies. The Chinese government supports green finance through regulatory measures, fiscal incentives, and public-private partnerships. Including green bonds, loans, and eco-friendly project investments (Tolliver et al., 2019; Bei and Wang, 2023; Sun et al., 2023). Empirical studies have demonstrated that China's green finance policies have indeed fostered the performance of green operations and corporate environmental responsibility, contributing broadly to the green transformation of the economy (Hu J. et al., 2021; Irfan et al., 2022; Huang et al., 2023; Zhang, 2023). Amidst the accelerating ageing, the emerging silver economy, aligned with China's low-carbon and ecological sustainability goals, could offer new domains for green finance.

When green finance intersects with the silver economy, there are many inherent interactions between these two concepts. The expansion of older population introduces new market demands, especially in healthcare, leisure, and housing modifications (Brink, 2023), spurring innovation and the emergence of markets like health management and smart home technologies (Selim, 2020). Their consumption patterns are significantly shaped by health, environmental awareness, and socioeconomic status (Menz and Welsch, 2012; Pais-Magalhães et al., 2022). For example, energy use typically increases during retirement compared to middle age, and in high-income countries, the elderly may prefer energy-intensive goods (Bardazzi and Pazienza, 2017). Their dependence on climate control systems like air conditioning and heating for comfortable living highlights the intersection of their needs with environmental concerns (Rhoades et al., 2017; Chang et al., 2022). One study suggests that retirement could lead to an annual increase of 1.71 billion kilowatt-hours in electricity use of China, representing 0.17% of national residential consumption (Zhu and Lin, 2022). Also, the essential need for accessible modifications is arising, such as in the U.S., where the lack of accessible facilities in bathrooms, has led to older adults incurring costs in the billions due to falls (Cisneros et al., 2016).

But from another point, older adults tend to prefer environmentally friendly and energy-efficient products and services, significantly contributing to the promotion of green consumption (Pillemer et al., 2021; Yin and Shi, 2021; Pais-Magalhães et al., 2022). Their preference for eco-friendly products and services, such as investment in solar energy equipment and household renovation, also older adults value the social prestige associated with their environmentally friendly actions, such as driving hybrid cars (Hur et al., 2015; Bardazzi and Pazienza, 2017). It is indicating a shift towards low-carbon development in related industries (as energy-efficient household products, healthy food, and green transportation) (Wrapson and Devine-Wright, 2014; Papadopoulos et al., 2016; Kim et al., 2018; Shahsavar et al., 2020; Li et al., 2024). Therefore, older adults possesses vast potential in promoting green production and lifestyles, their life experiences, combined with an acknowledgment of sustainable living and the need for a healthy environment, position them as active proponents of green lifestyles (Rhoades et al., 2017; Kriebel-Gasparro, 2022; Hampton and Whitmarsh, 2023). Their preference for green products can drive market demand towards more sustainable offerings, encouraging industries to innovate and adapt.

The growth of the silver economy in China is prompting the development of products and services tailored to older adults, which not only meet their unique needs but also drive market diversification and technological advancement. These emerging needs are where green finance can play a role. Moreover, China's modern urban and town development, guided by the principles of 'green, low-carbon, and ecological liveability' (Qiu et al., 2021; Chen et al., 2022), also including green construction and renewable energy use. The age-friendly modifications of infrastructure and housing must concurrently address eco-liveability (Frederick, 2022). Green finance can serve a key function in fostering these sectors, blending the silver economy's evolution with environmental sustainability.

3 Low-carbon innovation in the silver age: strategies and prospects

In the Silvering Anthropocene, integrating the silver economy and green finance is key to constructing an eco-friendly system in China. This integration uses the strengths to create a cohesive framework that addresses both the environmental and socio-economic aspects of ageing. China's first policy document on the silver economy clearly defines its key areas, including pension finance, geron-product innovation, smart elderly care industries, and age-friendly infrastructure modifications (General Office of the State Council Operation, 2024). While, pension finance is a key driver of China's silver economy (valued at approximately one trillion US dollars)

development, and both pension and green finance are focal points of financial initiatives under close government scrutiny (XinhuaPress, 2023). So, the integration of the silver economy with green finance is not only possible but also highly feasible. By deeply exploring the potential of green finance in contributing to the silver economy, combined with policy support and industrial innovation, new approaches can be developed to address the challenges of an ageing population. This exploration of integrated development models can also provide robust support for promoting the green and low-carbon transformation of the economy and society. Green finance as the enabler, can play a crucial role in funding these initiatives, providing the necessary capital for green technology development and incentivizing businesses to create eco-friendly solutions for older adults. Those green finance measures were concentrated on that can be utilized to boost the silver economy:

A. Investment in eco-friendly healthcare technologies: China's silver economy is large, with a significant need for innovative products. However, it is not well developed now, such as current internet-based caregiving platforms have not fully resolved caregiver market flaws (Hu Y. et al., 2021). Investments in geron-products, like accessible transport, would promote a low-carbon silver economy.
B. Funding energy-efficient housing for older adults: Ageing in place offers clear benefits, with U.S. data indicating that its integration with the sharing economy could halve the costs of elderly care (Miller et al., 2020). Yet, this requires accessible modifications. Green finance, potentially in combination with pension finance like reverse mortgages, can fund modifications in elderly-oriented housing, including sustainable heating and cooling systems that both meet seniors' comfort needs and help reduce energy use.
C. Promoting green lifestyle among older adults: China's policy framework advocates for dedicated zones for silver economy, including smart healthcare and elderly-oriented travel services. Also according to expert from the Asian Development Bank, developing age-friendly cities should be a key direction of China's green urbanisation (Rau, 2021). Thus, green finance should target sectors important to elderly lifestyles, such as investments in emerging retirement communities and the creation of carbon-neutral living spaces, promoting eco-friendly practices among seniors.

4 Conclusion

Investigating how to integrate the silver economy and green finance is vital for achieving the goals of sustainable development, especially to highlight the crucial role of ageing in fostering green transitions. We underscore the necessity of a multidimensional approach that blends economic, social, and policy innovations to align the welfare of older adults with environmental sustainability, amidst the challenges of the Silvering Anthropocene. Grounded in sustainable development and low-carbon transition theories, existed research have acknowledged the health benefits of the silver economy for older adults and their ability to influence communities through green lifestyles, but also overlooked the potential of green finance to drive the silver economy's low-carbon transformation (Kweon et al., 1998; Hong et al., 2018; Mason and Rigg, 2019; Ayalon et al., 2022). The integration of green finance into the silver economy could encounter social equity challenges, such as disparities between older adults' purchasing power and their willingness to buy specific products, alongside questions about the cost-effectiveness of these initiatives, necessitating further empirical exploration. Also, seniors might face difficulties using eco-friendly digital products, while elderly-oriented technology training could mitigate these risks (Zhang et al., 2023). As global challenges like ageing and climate action intersect more with the expanding silver economy, proactive strategies enhancing green finance's efficiency are crucial. If China could expand its application of green finance within the silver economy, it might provide valuable insights for the Global South, supporting the low-carbon transformation of the global ageing industry. This paper innovatively links green finance and the silver economy, emphasizing how demographic shifts can merge with eco-oriented green finance. By investing in green ageing product innovations, supporting environmentally oriented local elderly care, and building green communities, this approach could support low-carbon goals at the product-household-community level.

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Study on the effect of carbon trading on the carbon emission intensity of enterprises—a mechanism test based on ESG performance

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Facing the double constraints of the "double carbon" target and high-quality economic development, carbon trading policy is an important tool for realizing the emission reduction commitment; based on the perspective of microenterprises, the specific mechanism and spatial effect of carbon trading policy still need to be evaluated. Taking China's carbon emissions trading pilot as a quasi-natural experiment, this paper empirically investigates the impact of carbon trading policy on the carbon emission intensity of pilot enterprises and its mechanism of action, and its impact on the carbon emission intensity of neighboring enterprises, based on the multi-temporal double-difference model, moderating effect model, and spatial Durbin model with the A-share-listed enterprises in the period of 2009–2019 as the samples. It is found that: 1) Carbon trading policy will reduce the carbon emission intensity of enterprises to different degrees, and there are significant differences under different ownership types, degrees of marketization and the level of digitization. 2) Under the influence of environmental uncertainty, ESG disclosure will weaken the effectiveness of carbon emission reduction in the pre-pilot stage of the policy; with the gradual improvement of the carbon trading policy and ESG disclosure mechanism, ESG ratings will positively regulate the inhibitory effect of the carbon trading policy on the carbon emission intensity of enterprises through multiple paths. 3) Carbon trading policy effectively reduces multiple negative spillovers through the demonstration effect and competition effect of neighboring enterprises, driving the carbon emission reduction behavior of non-pilot enterprise. The research in this paper enriches the research paradigm of carbon emission intensity influencing factors, provides reference suggestions for the government to improve its policies, and better contributes to the realization of the "dual-carbon" vision in China as soon as possible.

KEYWORDS

carbon trading policy, ESG, corporate carbon abatement, multi-temporal double-difference, moderating effect, spatial spillovers

1 Introduction

In recent years, the climate problem caused by excessive carbon dioxide emissions has become a global issue affecting the survival and development of humanity (Cai et al., 2022a). Following the signing of the Paris Agreement, developed countries and regions such as the European Union, Japan, and Canada, which have already reached the peak of carbon emissions, have made a series of commitments to carbon neutrality (H. Wang et al., 2023), and will actively adopt the Clean Development Mechanism (CDM) and other policy instruments to reduce emissions (Sutter and Parreño, 2007). As a large carbon emitting country, China has taken the initiative to achieve carbon peak by 2030 and carbon neutrality by 2060, and set the "dual carbon" target as the national development strategy goal. However, the conflict between environmental protection and economic development is a major obstacle to China's sustainable development: economic development will inevitably lead to a close demand for energy (Cai et al., 2022b), and the large amount of energy inputs will certainly exacerbate the climate problem (Mohmmed et al., 2019). At the same time, China's traditional high-emission industries still account for a large proportion of the realization of carbon emission reductions will require China to accelerate the transformation of the industrial structure. In addition, urbanization and population growth brought out by economic development also make the implementation of carbon emission reductions difficult.

Under the ever-increasing pressure of resource and environmental constraints, how to reconcile the contradiction between the ecological environment and the improvement of the level of economic development has become a hot topic in today's society. Environmental economics believes that environmental problems arise from the negative externalities of the production behavior of the economic sector, and if the property rights of environmental public goods can be clearly defined, the market mechanism can be used to cure its own inherent deficiencies. In order to solve the problem of "dilemma conflict" problem, the "Kyoto Protocol" for the first time proposed the carbon emissions trading system - carbon pricing-based market incentives for enterprises to choose the appropriate investment methods or technologies to reduce pollutant emissions. The carbon pricing-based market incentive mechanism provides greater flexibility for enterprises to choose appropriate investment methods or technologies to reduce pollutant emissions. To further promote carbon emission reduction measures, China has actively invested in the exploration of ETS research and the construction of voluntary emissions trading market. In October 2011, the National Development and Reform Commission issued the "Notice on Carbon Emission Trading Pilot Work", which approved seven provinces and municipalities, including Beijing, Shanghai, Tianjin, Chongqing, Hubei, Guangdong and Shenzhen, and announced the opening of the national carbon trading market in June 2021. According to statistics, China's carbon emission intensity has decreased significantly since 2013. By 2020, China's carbon emission intensity will have decreased by 18.8 per cent compared with 2015 and 48.4 per cent compared with 2005, exceeding its international commitment targets. Carbon trading, as an economically effective and important policy system, can influence the carbon emission intensity of pilot enterprises and neighboring enterprises by adjusting industrial structure, optimizing energy structure and enhancing innovation.

To address the negative impact of the uncertain economic environment on business decisions and investment strategies, the inclusion of a public interest component in the corporate value system is more in line with current policy needs. As a result, companies' environmental, social and corporate governance (ESG) performance has become an important criterion for measuring their level of sustainable development of enterprises. In 2008, the SSE and the SZSE successively required enterprises to disclose reports on their social responsibility performance as part of the annual report disclosure in the Circular. In recent years, the level of ESG disclosure domestic companies has improved, and the disclosure rate of A-share ESG reports will be 34% in 2022, an increase of 3% compared to 2021, and listed companies are increasingly becoming "activists" to help carbon reach the peak and become carbon neutral. Analysed from the perspective of political motivation, ESG can significantly improve corporate social responsibility and promote green transformation through market incentives and external monitoring mechanisms, thus promoting green and low-carbon development of enterprises. From the perspective of political motivation, (Ji et al., 2023) found that ESG disclosure can reduce the impact of financial risk on companies, and Dhaliwal et al. (2011) found that ESG disclosure can improve information transparency to reduce the transaction costs of enterprises and alleviate the problem of financing constraints. Analyzing from the perspective of investor motivation, there are cases of whitewashing and avoidance of shortcomings in traditional financial reports, from which investors are difficult to obtain effective information for deciding their investment intentions, and high-quality ESG reports are more helpful for their decision-making (Svanberg et al., 2022).

The marginal contributions of this paper are as follows: 1) Scholars mainly focus on the policy pilot regions, and pay less attention to the real policy intensity and governance effects on the first pilot enterprises (J. Hou et al., 2024; Xian et al., 2024). This paper takes the enterprise perspective as the starting point, providing reference basis for the carbon emission reduction of enterprises and the technological transformation of neighboring enterprises, further promoting the decarbonization and greening of industries, and allowing more enterprises to participate in the practice of realizing the "dual-carbon" strategic goal. 2) The analysis of the spatial effect of the carbon trading policy on pollution control is mostly focused on the region (Chang and Zhao, 2024; K. Li et al., 2024), and there is almost no research focusing on the flow of policy effects among micro enterprises, so a more accurate assessment of the actual policy effect among enterprises is lacking. This paper contributes to the analysis of the vertical and horizontal development of the policy's carbon emission reduction effect of the policy, enriches the research paradigm about the influencing factors of carbon emission intensity in time and space effects, deepens the understanding of the impact of the carbon trading policy among enterprises and its path of action, and deepens the research on the evaluation system of environmental policies. 3) In the analysis on the effects of the carbon emissions trading policy, fewer studies have been conducted to deeply analyze the specific role path of the policy around the role

of the mechanism of corporate ESG disclosure (Tian et al., 2024; Wan et al., 2024). This paper will provide a reference basis and feasible suggestions for the government to improve the policy and regulation of corporate ESG disclosure, draw the government's attention to the correlation effect of the enterprise policy and put forward new ideas, and provide a clear guidance for China's progress towards the goal of peaking carbon emissions. 4) In the testing the policy effects, a large number of studies have adopted double-difference models (Y. Chen and Mu, 2023; X. Feng et al., 2024a), and fewer studies have analyzed the spatial spillover effects of pilot policies by combining double-difference models, moderating effect models, and spatial econometric models. Therefore, this study examines the policy effects of the carbon trading policy on the carbon emission intensity of the first pilot enterprises over time and space from the perspectives of "between pilot enterprises - between government and enterprises - between enterprises and enterprises"; and examines the policy effects of the carbon trading policy on the carbon emission intensity of the first pilot enterprises over time and space with the help of the enterprises' internal environmental management practices—ESG disclosure, in order to explore the specific path of carbon emissions trading, so as to enhance the carbon emission reduction capacity of enterprises, to achieve the construction of ecological civilization and sustainable economic and social development, and to better contribute to the realization of China's vision of peaking carbon emissions by 2030.

2 Literature review

2.1 Literature on the influence factors of carbon emission intensity combing

With China's increasing attention to corporate carbon emissions, the academic community has adopted various methods to measure the factors affecting carbon emission carbon intensity. By organizing and analyzing the existing research results, energy consumption and economic growth are the main driving factors of carbon emissions intensity (Esso and Keho, 2016; Nain et al., 2017; Rehman and Rashid, 2017; Osobajo et al., 2020). In tearms of energy consumption, (Zhang and Cheng, 2009) found a positive correlation between energy consumption and carbon emissions by using vector autoregression (VAR) and error correction model (ECM). Abdallh (2017) and others took the EKC approach, and further found that energy consumption is the main source of carbon emissions. Xiao et al. (2019)integrated the spatial lag model and spatial error model, and found that industrial structure, energy intensity, energy price and degree of openness are the main influencing factors of carbon emission intensity and carbon spillover. Zhao et al. (2018) used the LMDI method to decompose the influencing factors of carbon emission changes in six types of industries into emission factors, energy structure, energy intensity and industrial scale. Among them, energy structure plays a positive role in the process of carbon emission reduction in industries such as industry and construction, and plays a negative role in agriculture, transport and trade industries.

From the perspective of economic growth, Xu et al. (2021) concluded that gross product, research and development, foreign direct investment, and urban built-up area are the main factors influencing China's CO2 emissions. Based on different regional panels, Wang (2017) suggested that: in terms of the cumulative effect at the national level, the effects of population, economic output, industrial structure, and energy structure have a positive impact on the increase in carbon emission intensity; at the provincial level, the economic output effect is the main positive factor driving the change in carbon emission intensity. In addition, Baiocch et al. (2010) showed that carbon emissions are positively correlated with income, controlling for lifestyle and other determinants. Some studies have further verified that the relationship between *per capita* income and carbon emissions is consistent with the EKC hypothesis that environmental quality may undergo an inverted U-shape transformation process as economic growth and *per capita* income increase. Combined with the new economic forms at the current stage, Li (2022c) and others used the SDM model and the panel threshold model for nonlinear analysis to conclude that the digital economy also has an inverted U-shaped relationship with carbon emissions.

2.2 Researches on the emission reduction effect of carbon trading policies

Based on the innovation-driven theory, Porter believes that environmental regulation can force enterprises to take the initiative to carry out technological innovation in order to reduce production costs and improve carbon production efficiency. Among them, the cost of compliance effect usually occurs in the current period, while the innovation compensation effect has a certain time lag (M. Porter, 1996). Based on this, Acemoglu et al. (2012) consider the interaction between environmental policy and technological innovation, and through the construction of a dynamic model, they found that the strengthening of environmental policy will increase the demand for environmentally efficient technologies, and such technological innovation will further reduce the demand for environmental resources by enterprises, forming a feedback loop between the environment and technological innovation. The results also suggest that the direction of firms' technological innovation will be influenced by environmental policy. In a further study, Dechezleprêtr (2017) constructs a balanced panel by collecting data on industrial sectors globally, and finds that strict environmental regulations can promote innovation activities of firms, especially in technology-intensive industries. Dechezleprêtre and (Wang et al., 2020) jointly show that technological innovation has a significant impact on the reducing carbon emissions in high-technology-intensive industries. Calel and Dechezleprêtre (2016) study the specific pathways and find that environmental regulations stimulate firms to undertake technological innovation and research and development in order to find environmentally friendly solutions; the study also finds that there is a certain degree of heterogeneity in the impact of environmental regulations on innovation, and the impact of environmental regulations on innovation is more pronounced in high-polluting industries and large firms. In summary, environmental regulation can be an effective policy tool to

promote innovation. Governments can incentivize firms to innovate and promote environmentally friendly technologies and solutions by formulating and implementing environmental regulations.

Based on the cost-constraint theory, Coaserh (2012) and Tietenberg (1985) argue that when transaction costs are zero and property rights are clearly divided all firms will bear the same marginal abatement costs, and environmental regulation through market-based instruments rather thanthe command approach can achieve Pareto optimality. Among them, price constraints can induce economic agents to reduce emissions in areas with lower carbon abatement costs, while quantity constraints can ensure that overall carbon emission reduction target can be achieved. Pizer (2002) proposed that combining price control (e.g., carbon pricing) and quantity control (e.g., carbon quotas) can improve the effect of carbon emission reduction based on this. However, Abrell (2011) and others suggest that although the carbon trading system can help reduce carbon emissions, it has less impact on the performance of participating enterprises, and may even increase the management costs of enterprises. Goulder and Schein (2013) further point out that the implementation and regulation of carbon trading policies are more complex, and may face problems such as market manipulation and price volatility and have an impact on enterprise performance. However, the mainstream view in the academic community confirms the effectiveness of the carbon regulatory system to reduce emissions from the financing costs, decision-making costs, and agency costs: in terms of debt costs, carbon-intensive enterprises will bear a greater violation of the emission costs and the risk of default emissions (Ren et al., 2023); in terms of decision-making costs, carbon trading policy can be used to alleviate the constraints of innovative financing by improving the accuracy and transparency of information (Ferrer et al., 2019); in terms of agency costs, stakeholders can realize low-cost regulation of climate physical risks and governance performance through market signals (Rose et al., 2005), and the negative relationship between agency costs and trading prices will increase the incentives for firms to enter the carbon market (Zhu, 2017).

With regard to the emission reduction effect of carbon trading policy, some scholars take the opposite view: due to the existence of the "green paradox", "bottoming out competition" and other phenomena, the carbon emission reduction effect of carbon trading policy may have a negative spillover. The "green paradox" refers to the idea that the restrictive effect of environmental regulations will have a crowding out effect on economic efficiency, leading to an increase in the supply and accelerated consumption of fossil energy, and ultimately leading to an increase in carbon emissions and a further deterioration of the environmental situation. On this basis, Van der Werf and Di Maria categorize the green paradox effect into two versions - weak and strong: the weak version emphasizes that imperfect climate policies increase carbon emissions in the short term, while the strong version emphasizes the increase in the net present value of future losses from climate change (Van der Werf and Di Maria, 2012). In terms of "bottom-up competition", top-down Chinese scale competition will result in a series of forms of competition, such as spending competition, tax competition, environmental regulatory competition, etc. (Rudra, 2008), of which spending competition will squeeze out environmental protection inputs (G. Porter, 1999), This has led to the convergence of local governments' policies of insufficient environmental protection investment; in this regard, Zhang utilized the environmental expenditure data of 284 prefectural-level cities in China to confirm that China's environmental expenditures have been caught in the predicament of "competition at the bottom" (Z. Zhang et al., 2020a).

The above research shows that the carbon trading mechanism can effectively enhance the liquidity of the carbon market and the flexibility of carbon rights allocation, and realize the reduction of carbon emissions intensity while effectively enhancing the value of enterprises. Among other things, the key to policy design lies in balancing economic efficiency and emission reduction, and the establishment and operation of the carbon trading market requires a high degree of regulation and supervision to ensure the fairness and transparency of transactions.

2.3 Analysis of the role mechanism regarding ESG disclosure

Feng He (2022) and others believe that managers' motives for ESG participation can be categorized into two types: self-interest motives and sustainable development motives. Among them, ESG disclosure strengthens the awareness of corporate value creation and sustainable development by influencing corporate financial performance, corporate social responsibility and managerial behavior. Based on the perspective of corporate financial performance, Henisz (2019) and others identified five main ways in which ESG is associated with corporate value creation: promoting revenue growth, reducing costs, minimizing regulatory and legal interventions, improving employee productivity, and optimizing investments and capital expenditures. Freeman (2010) demonstrated that investing in ESG activities can enable firms to gain a competitive market advantage and improve financial performance. performance.

Chen Meng-tao (2023) et al. further suggest that ESG disclosure can serve as an additional positive signal to improve stock liquidity through the institutional investor preference channel and the risk mitigation channel. However, results on the relationship between firms' ESG performance and financial performance are mixed. Awaysheh (2021) et al. find that many of the higher scoring ESG portfolios underperform the market, while some of the lower scoring ESG portfolios outperform the market through the use of US market stocks. However, in the long run, Hui Wen (2022) used a baseline model of Tobin's Q to confirm that the quality of ESG disclosure has a significant effect on increasing the market value and financial returns of firms as well as reducing the financial risk of firms. Meanwhile, Mario Testa found after empirical analysis that the relationship between financial performance and environmental performance is a mutual interaction and causality (Testa & D'Amato, 2017), so that the improvement of financial performance will further promote the attention of enterprises to environmental performance.

Based on the CSR theory, Feddersen (2001) and others found that companies with potential growth opportunities may receive more strategic investments and benefits from CSR activities, effectively increasing the demand for CSR activities. Minor (2010) and others argued that CSR activities can provide

companies with goodwill and ethical capital, and will provide insurance-like protection in the event of adverse events. Berman et al. (1999) further suggest that reputation as a valuable resource reduces the severity of damage to firms in the event of business shocks and mitigates the likelihood of unfavorable regulatory, legislative, or fiscal action; meanwhile, while Waddock (1997) argues that firms need to offer the market a promise of quality and assurances of differentiation in order to create a competitive advantage. When analyzing the indirect effects, Mishra et al. (2017) used CSR as a mediator to demonstrated that innovative firms may enhance the value effect of their innovation efforts by promoting social responsibility, i.e., firms may seek higher ESG performance after innovation in order to develop valuable reputational resources and reduce capital constraints. In addition, there is no academic consensus on the stakeholder and resource base theories, which suggest a positive link between CSR and firm performance, and the neoclassical theory, which suggests that CSR imposes additional costs on firms and diverts funds from profitable investments.

Based on the theory of managerial behavior, more scholars focus on corporate governance and green innovation. Regarding the impact of ESG disclosure on corporate governance, Ren (2022), Zaman (2021) and others suggest that ESG performance has a substitution effect on internal and external corporate governance: high-quality ESG performance can inhibit managerial misbehavior by attracting the attention of analysts and brokers to create a good external monitoring environment. At the same time, ESG can strengthen internal governance by mobilizing independent directors and further regulating managerial behavior. However, some scholars hold opposite views: Jensen (2019) suggests that CSR practices based on opportunistic incentives to participate may mislead stakeholders' perceptions of firm value and financial performance; Hemingway (2004) further suggests that managers may cover up their misbehavior by actively participating in ESG activities, and that in a high reputation insurance situation, managers are more likely to be involved in ESG activities, and in the case of higher levels of reputation insurance, managers are more likely to be involved in ESG activities. Situation, managers are more likely to adopt risky behaviors that satisfy the fraud triangle (Cressey, 2017). Regarding the impact of ESG on corporate innovation behavior, most studies show that ESG disclosure is positively correlated with corporate innovation. Now academic research on this facilitating effect mainly focuses on the following mechanisms: 1) External monitoring mechanism: Wang et al. (2023) suggest that ESG disclosure can force enterprises to carry out green innovation by reducing external monitoring costs. 2) Mitigating information asymmetry: ESG disclosure can incentivize firms to innovate by reducing innovation risk. 3) Increase resource availability: Wu et al. (2023) used the double-difference method to confirm that ESG disclosure mainly improves firms' innovation level through the two paths of "patent-driven" and mitigating the "crowding-out effect", using the financial constraint index as a mediating factor, found that ESG disclosure promotes green innovation by reducing corporate financing constraints, and this performance is more significant in non-green and high-tech industries dominated by strong technological motives (Bilyay-Erdogan, 2022; L. Chen et al., 2023a). However, some scholars, based on traditional agency theory, argue that excessive disclosure of ESG information is a resource crowding behavior motivated by the maintenance of managers' reputation.

3 Theoretical analysis and research hypothesis

3.1 The direct impact of carbon trading policy on the carbon emission intensity of enterprises

Carbon trading policy, as a flexible and efficient market-based emission reduction tool, privatizes carbon emissions through the establishment of a property rights system and uses carbon price signals to guide the optimal allocation of emission reduction resources in the economic system, thus achieving the dual goals of environmental and economic benefits. According to the data, since the launch of the carbon trading pilot in 2013, China's carbon emission intensity has dropped significantly, and in 2017 China's carbon emissions dropped by 5.1% compared with 2016. In addition, compared with 2005, carbon emissions in 2017 were reduced by about 46 percent. In the carbon trading market, enterprises are both the microscopic subjects of carbon emissions and the direct objects of the effects of carbon trading policies. Micro-enterprises are driven by interests to realize carbon emission reduction in two ways, namely, saving costs and increasing revenues.

Based on the cost constraint theory, in the tangible cost, if inefficient emitting enterprises do not explore ways to reduce emissions, the following three consequences will result. First, the excess carbon emissions under the established production target, inefficient emitting enterprises must bear the additional expenditure of purchasing carbon allowances from efficient emitting enterprises. Second, if enterprises in the pilot region make decisions to reduce production under the established carbon emission constraints, they will have to bear the loss of profits due to the decline in production. Third, if they emit more than they should, they run the risk of being penalized and paying the price for polluting the environment. But in either case, the tangible costs of inefficient emitters will rise, weakening their market competitiveness. At the same time in terms of intangible costs, inefficient emitters will receive lower valuations in the market compared to efficient emitters, which will be more favored by investors. Obviously, high-efficiency emitting enterprises will be more advantageous in terms of cost. Thus, it can be seen that the implementation of carbon trading policy makes high-emission enterprises face the problem of cost increase, which exerts economic pressure on them and forces them to explore the path of carbon emission reduction, so as to realize the overall effect of carbon emission reduction. Enterprises are forced to reduce their carbon emissions through technological innovation, industrial structure adjustment and improvement of resource utilization efficiency. Although technological innovation will bring new costs to enterprises, scholars have verified the weak Porter effect based on Porter's hypothesis (M. E. Porter and Linde, 1995a): even if there is an increase in the cost of innovation, enterprises can still realize that the new benefits are greater than the new costs (Zhong et al., 2023). Therefore, rational enterprises will choose technological innovation to promote emission reduction instead of facing the problem of purchasing

carbon allowances or paying fines for excessive emissions. The synthesis of the above analysis can be concluded that from the perspective of cost constraints, enterprises will be affected by the carbon trading policy to reduce their carbon emission intensity.

Based on the theory of environmental economics, firstly, enterprises that meet the carbon emission standards can avoid paying carbon taxes and penalties, thus reducing their operating costs. Second, the implementation of the carbon trading policy provides new business opportunities for enterprises, and the sale of surplus allowances allows them to increase the price of carbon trading in order to obtain excess profits and cash inflows (Veith et al., 2009). Furthermore, with the increasing demands for sustainable development, enterprises are gradually realizing the importance of reducing emissions: participating in carbon trading and reducing carbon emission intensity will help enterprises establish a good environmental image and improve their competitiveness in sustainable development. According to stakeholder theory, this will better maintain the relationship network between enterprises and stakeholders, create competitive advantages for enterprises and bring intangible benefits (X. Zhang and Zheng, 2024). Therefore, in order to increase revenue, enterprises will choose to actively pursue low-carbon production, carry out innovative activities of low-carbon technology and efficiently utilize energy so as to reduce carbon emissions. In addition, the increase in the cost of carbon emissions will increase social investment in low-carbon products and industries, improve the efficiency of enterprise resource allocation and optimize the industrial structure; (Nayyar et al., 2014) pointed out that the carbon trading policy can promote the faster transition to clean energy and upgrading of industrial structure by adjusting the demand structure. Therefore, carbon trading policy has the effect of carbon emission reduction in the perspective of promoting economy (X. Feng et al., 2024a).

Based on the above analysis, this paper puts forward the research hypothesis.

H1: Carbon trading policy has an inhibitory effect on carbon emission intensity in pilot regions.

3.2 The mechanism role of ESG disclosure level in the impact of carbon trading policy on carbon emission intensity

With regard to the analysis of the policy mechanism, carbon trading policy is an effective policy tool to optimize the allocation of carbon emission resources, reduce the cost of carbon emission reduction, and control greenhouse gas emissions. However, in the quasi-natural experiment of the pilot policy, carbon trading still needs to be improved in terms of market effectiveness and the ability of coordinated management of regulatory resources (Yang, 2023), and the ESG disclosure system is still in an imperfect stage at the early stage of the pilot program, and the incompatibility between the carbon trading policy and the ESG disclosure mechanism may weaken the emission reduction effect of the policy. According to the signaling theory, the increase of environmental uncertainty will increase the difficulty of enterprises to formulate strategies. In this case, companies are more inclined to enter high-carbon fields with lower cost and technology thresholds, ignoring ESG concepts such as environmental governance and social responsibility. Driven by environmental uncertainty and lack of regulation, firms may implement a series of undesirable competitive strategies, such as commercial bribery, false public goods, and corporate greenwashing to reduce their environmental governance costs (Dhole et al., 2021; Hou et al., 2021), resulting in an asymmetry between economic and actual environmental benefits (Wang et al., 2023). Meanwhile, a high degree of environmental uncertainty will lead to an increase in investment waiting options and risk aversion, exacerbating the financing constraints of corporate green innovation and causing a downward trend in environmental performance (Z. Chen et al., 2022). In addition, the conflict between ESG performance and sustainability commitments will damage the market value of firms by affecting their goodwill, which in turn will cause disruptions to the operation of the carbon market (S. M. Fazzari and Athey, 1987).

With the gradual improvement of carbon trading policy and ESG disclosure mechanism, ESG disclosure policy can promote carbon information transfer and carbon market liquidity, while driving the fulfillment of corporate social responsibility from internal and external sources to further enhance the carbon emission reduction effectiveness of the policy. Specifically, ESG may promote policy emission reduction through paths such as reducing information asymmetry, improving carbon information quality, and enhancing monitoring pressure. Based on the signaling theory, companies communicate their organizational image, intentions, behaviors, and performance through signals, thus reducing information asymmetry and data authenticity issues in the carbon trading process (Karaman et al., 2020). It can be seen that more stringent carbon emission measurement methods and carbon accounting systems in ESG disclosure mechanisms can improve the carbon information disclosure system and quantitative norms, and enhance the transparency and bargaining power of carbon information. At the same time, according to the principal-agent theory, environmental regulation and managers will constrain the negative externality of enterprise operation through the formation of internal and external supervision system, thus positively promoting the carbon emission reduction effect of carbon trading policy. As a result, in the policy context of carbon trading, ESG disclosure can avoid the problem of "localized emission reduction, overall pollution diffusion and exacerbation pattern", i.e., the "pollution paradise hypothesis", by strengthening the regulatory constraints on synergistic emission reduction (S. Li et al., 2022). In addition, according to the theory of financing superiority, poor information is the key issue leading to corporate financing constraints, and ESG information disclosure can reduce the level of corporate financing constraints to promote innovation effects of carbon trading policiescorporate innovation by enhancing the willingness of investors to invest and confidence, which in turn improves corporate productivity and reduces the intensity of carbon emissions (H. Wen et al., 2022b). At the same time, lower financing constraints will also increase the willingness of enterprises to take risks to a certain extent, which will inhibit their risk aversion to green investment (Maaloul, 2018).

Based on the CSR theory, ESG disclosure may facilitate policy reductions through the paths of stakeholders, reputational capital, and green innovation: according to the theory of corporate social responsibility, economic, legal, ethical, and philanthropic

responsibilities constitute the pyramid of corporate fulfillment of social responsibility (Carroll, 1991); furthermore, Bowen defines it as the obligation of a company to pursue desirable policies in terms of social goals and values (Azimli, 2023). Stakeholder theory suggests that enterprises will no longer be able to limit themselves to the perspective of shareholders' interests, but will need to consider the legitimate needs of stakeholders, including the environment, society, and the economy; at the same time, corporate responsibility behavior is seen as a tool for its own reputation management and brand protection (Lewis, 2003), and a good corporate image can strengthen the stable relationship with external stakeholders, and obtain stable social capital. As a result, ESG disclosure is actually an incentive and penalty mechanism for corporate carbon emissions, which serves as an internal driver to improve corporate carbon emission reduction initiative and corporate value-innovation performance and environmental governance level, etc., and prompts corporate managers to set corporate development goals based on the concept of sustainability. In addition, the traditional agency theory and follow the cost theory that part of the environmental regulation will take away from the enterprise plan resource allocation (Y. Li et al., 2023), and ESG disclosure can amplify and promote the positive externalities of innovation for responsible innovation, providing new opportunities for the sustainable development of enterprises.

Based on the above analysis, this paper proposes the hypothesis.

H2: In the pre-pilot period of the policy, ESG disclosure plays a negative moderating role in the path of carbon trading policy on carbon emission intensity; in the late period of the policy pilot, ESG disclosure plays a positive moderating role in its path of action.

3.3 Influence of carbon trading policy on carbon emission intensity of enterprises in neighboring areas of the pilot region

From the theory of externality, it can be seen that externality is a kind of spillover effect in economic activities, and the behavior and decisions of enterprises will have external effects on their surrounding environment. However, externalities are divided into positive and negative externalities, which leads to the diversity of spatial spillover effects, including both positive and negative spillover effects. Extending to the implementation of carbon trading policy, under the spatial perspective, it can be considered that the carbon trading policy acting on the pilot enterprises has spillover effects on the neighboring enterprises. Comprehensively, since the implementation of the carbon trading pilot policy, scholars have explored the spatial spillover effect at the provincial level and city level, and confirmed that the carbon trading policy generally shows more positive than negative spillover effects (Dhole et al., 2021; Hou et al., 2021). On this basis, this paper argues that based on the spatial spillover effect, neighboring enterprises are also affected by the carbon trading policy to produce carbon emission reduction effect, and the carbon emission reduction effect still exists when summed up to the overall perspective.

From the perspective of positive impacts, as the enterprises in the pilot area are regulated by the policy, they will spontaneously carry out low-carbon technological innovation, industrial structure adjustment, new energy application and other decisions (Z. Li et al., 2022), which will have demonstration effects and warning effects on the neighboring enterprises. The demonstration effect is mainly manifested in the technological spillover of low-carbon technologies, and neighboring enterprises can accumulate innovation and management experience from the technological innovation activities of the pilot enterprises, thus promoting carbon emission reduction of neighboring enterprises. The warning effect is mainly reflected in the long-term trend of the carbon trading policy, which is likely to be extended from the pilot region to the whole country. Neighboring enterprises will definitely consider the orientation of the policy when formulating development strategies, which will be manifested in their technological innovation and learning to adapt to the policy in advance, and consider the long-term interests and adaptability of their enterprises. In addition, based on the theory of linkage effect, regional linkage between regions or markets can generate induced investment and expand the whole industrial chain through expansion (Su et al., 2024); meanwhile, the difference in technological progress to promote the flow of production factors from low productivity to high productivity flow is conducive to the upgrading of industrial structure (Yan et al., 2024). Based on signaling theory, interregional information exchange can realize the spillover effect of policy emission reduction by reducing the cost of resource matching and increasing financial support (Y. Huang et al., 2022).

In terms of negative impacts, because of the relatively lax policies of neighboring regions in the pilot areas, there is a risk that high-polluting and high-emission industries may evade policy regulations by moving to neighboring regions or outsourcing high-polluting production to neighboring enterprises (Dai et al., 2022a). At the same time, small and medium-sized enterprises (SMEs) face a more competitive environment, and SMEs in the pilot areas may face unfair competition, a factor that may also lead to the transfer of pollution to neighboring areas. Such pollution transfer will greatly reduce the effect of the policy and aggravate carbon emissions in neighboring areas, which is against the original purpose of the carbon trading pilot policy.

Based on the above analysis, this paper puts forward the hypothesis.

H3: The carbon trading policy has an inhibiting effect on the carbon emission intensity of neighboring enterprises in the pilot area.

Based on the above, the research framework is presented in Figure 1.

4 Model construction and variable selection

4.1 Model construction

4.1.1 Benchmark regression with double differences (DID)

As a "quasi-natural experiment", the carbon emissions trading policy pilot has randomness, so it is more suitable to use the method of Zhang (2021) to choose the double-difference model to analyze the effectiveness of the policy. The specific formula is shown in Eq. 1, where i, r, t represent enterprises, regions and time, respectively. The

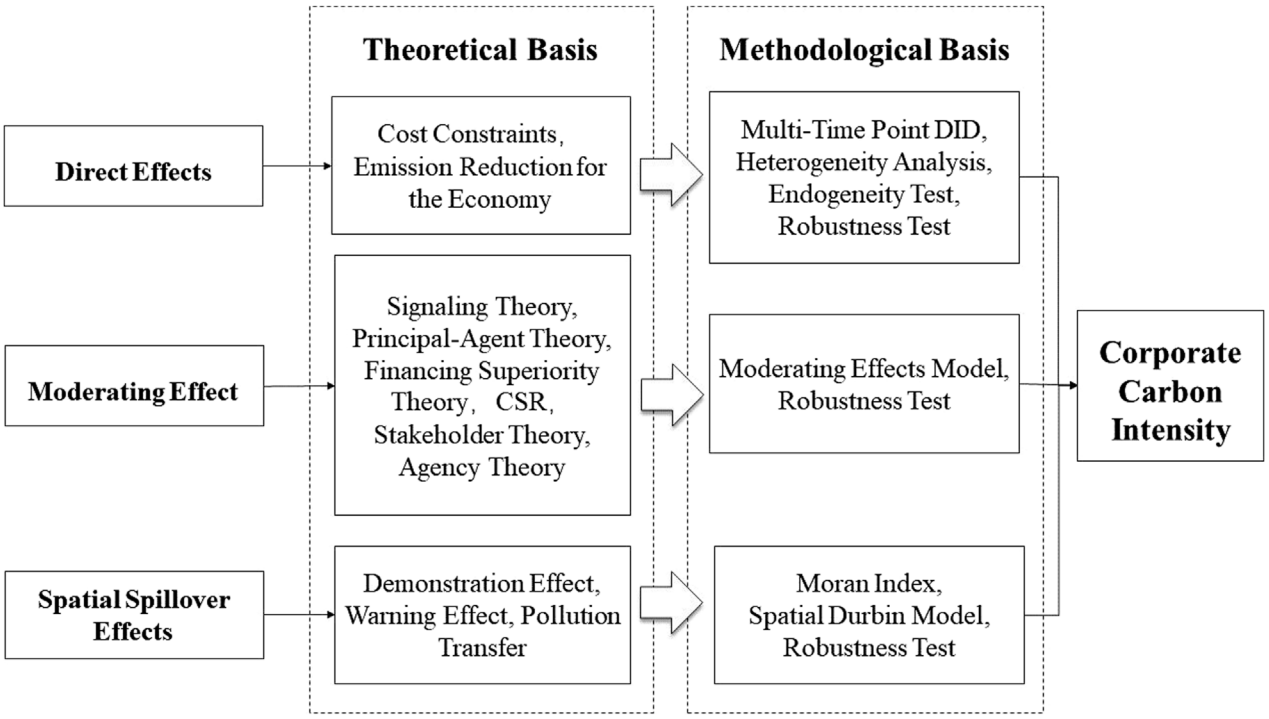


FIGURE 1
Theoretical model.

explanatory variables of the model are the cross-multiplication terms of the policy pilot time dummy variable and the policy pilot region dummy variable. *Cbtradet* denotes whether r region started the carbon emissions trading pilot work in year t. The year r region started the carbon emissions trading and the years thereafter take the value of 1, otherwise it takes the value of 0; *Pilotr* denotes the dummy variable of the pilot region, which takes the value of 1 if it is a policy pilot region and 0 otherwise; *X* is the ensemble of firm-level control variables; μi is the firm fixed effect; ηt is the time fixed effect; and ε is the randomized disturbance term.

$$CEIirt = \alpha 0 + \alpha 1 Cbtra\,\det \times Pilotr + \theta Xirt + \mu i + \eta t + \varepsilon irt \quad (1)$$

4.1.2 Moderated effects model

In this paper, we adopt the approach of Feng (2022), which is based on the DID model with the addition of the moderating variable *ESG* and the interaction term between the moderating variable *ESG* and *DID*, and the specific model is shown in Eq. 2:

$$CEIirt = \alpha 0 + ESG + ESG \times DIDirt + \alpha 1 Cbtra\,\det \times Pilotr + \theta Xirt + \mu i + \eta t + \varepsilon irt \quad (2)$$

4.1.3 Moran index test

Before deciding to use the spatial panel model, this paper will use the Moran index I and construct a matrix geographic distance matrix to test the spatial autocorrelation of the carbon trading policy. Among them, the local Moran index is used to examine the spatial aggregation near the pilot area of the policy, and its formula is Eq. 3:

$$Ii = \frac{xi - \mu}{\sigma} \sum_{j=1}^{n} Wij(xi - \mu) \quad (3)$$

Where *Ii* represents the localized Moran index of the ith province, *xi* the carbon emission intensity of the ith province, μ is the mean of the carbon emission intensity of the 30 provinces, σ is the standard deviation of the carbon emission intensity of the 30 provinces, *Wij* is the value of spatial weights, and n is the total number of all the provinces, i.e. 30.

4.1.4 Spatial durbin model

Based on the method of Amidi (2020), this paper further constructs the spatial error model (SEM), spatial autoregressive model (SAR) and spatial Durbin model (SDM) to evaluate the spatial spillover effect of the carbon trading pilot policy. At the level of research ideas, according to Perrox's "growth nucleus" theory, regional development and enterprise development are not carried out at the same time, but through the enterprise's own development and then spread to the surrounding areas, so this paper will be different from the existing research, from the enterprise micro perspective, extended to the macro-provincial perspective; at the same time, taking into account the possible impact on the results of the difference in latitude and longitude between units of enterprises is too small, this paper will be different from the established research, from the enterprise micro perspective to the macro-provincial perspective. At the same time, considering the possible influence of small latitude and longitude differences between enterprises, this paper sums up the enterprise panel data to the provincial level to establish a spatial geographic matrix, and conducts a regression on the panel data of a total of 30 provinces

(excluding Hong Kong, Macao, Taiwan, and Tibet) in order to more comprehensively detect the policy effects of the carbon trading pilot. The specific formula is Eq. 4:

$$\begin{aligned} CEIrt &= \alpha 0 + \alpha 1 DIDrt + \theta Xrt + \lambda W \varepsilon rt + \mu r + \eta t + \varepsilon rt\,(SEM) \\ CEIrt &= \alpha 0 + \alpha 1 DIDrt + \theta Xrt + \rho WCEIrt + \mu r + \eta t + \varepsilon rt\,(SAR) \\ CEIrt &= \alpha 0 + \alpha 1 DIDrt + \theta Xrt + \varphi WXrt + \rho WCEIrt + \gamma 1 WDIDrt \\ &\quad + \mu r + \eta t + \varepsilon rt\,(SDM) \end{aligned} \tag{4}$$

Where W is the weight matrix describing the spatial adjacency of the region; μ denotes obeying a normal distribution; λ and ρ denote the spatial correlation strength and the spatial correlation coefficient, respectively; and the rest of the variable definitions are consistent with each other.

4.2 Variable definitions and data description

(1) Explanatory variables: the cross-multiplier of the carbon emissions trading pilot policy and the dummy variable for pilot regions (*DID* or *Cbtradet*Pilotr*). Considering the differences in the time point of the implementation of the policy in each pilot region, this paper adopts the multi-period DID method for regression analysis, which divides Shenzhen into the beginning of 2013, Shanghai, Beijing, Guangdong, Tianjin, Hubei, and Chongqing into the beginning of 2014, and Fujian Province into the beginning of 2017 (Bian et al., 2024; Q. Wu, 2024).

(2) Explained variable: enterprise carbon emission intensity (*CEI*). According to the Intergovernmental Panel on Climate Change (IPCC) carbon emission accounting method to calculate the municipal panel carbon dioxide emissions, and combined with Jing Wu et al. (Wu et al., 2022; Wang et al., 2023)'s method to calculate the emission coefficient of each enterprise, so as to get the carbon emissions of each enterprise in the whole country, and finally divide the carbon emissions of the enterprise by the amount of its corresponding business income to get the enterprise carbon emission intensity, the specific formula is as follows:

① The carbon emission adjustment factor is first calculated for each prefecture-level city as in Eq. 5:

$$Wi = \sum \frac{Pi/\sum Pi}{Oi/\sum Oi} \tag{5}$$

② Then the carbon emissions of i prefecture-level cities are calculated as in Eq (6):

$$emi = W\mathrm{i} \times Y \tag{6}$$

③ Finally, the formula for the emissions of pollutant j from firm k in county i is Eq. 7:

$$emik = emi \times \frac{\mathrm{Ok}}{\sum Ok} \tag{7}$$

Where Pi is the carbon emission of prefecture i, $\sum Pi$ is the national total emission of carbon dioxide; Oi is the total industrial output value of prefecture i, $\sum Oi$ is the national total industrial output value; Yi is the original emission of carbon dioxide of prefecture i; Ok is the industrial output of enterprise k, and $\sum Ok$ is the total industrial output of the prefecture where the enterprise is located, and in this paper, we use the amount of business revenue of the enterprise as a proxy for the enterprise's industrial output.

(3) Moderating variable: ESG disclosure level (*ESG*). Quantitative ESG scores are derived from three factors: environmental practices, social practices, and transparency and disclosure of corporate governance. Based on related literature (Liu et al., 2023; Gupta and Kashiramka, 2024), the annual composite score of ESG ratings is a common indicator of the level of ESG sustainability disclosure, and the score is proportional to the level of ESG disclosure. At present, the domestic ESG rating system shows a diversified development, mainly including CSI ESG rating, Shangdao Ronglv ESG rating, Runling Global ESG rating, etc. Compared with other rating systems, CSI ESG rating data has the advantage of being close to the Chinese market, covering a wide range of time-sensitive data. Compared with other rating systems, CSI ESG rating data has the advantages of being close to the Chinese market, covering a wide range of areas, and having a high degree of timeliness; at the same time, CSI has formulated corresponding indicator systems for different industries, which makes ESG evaluation more refined. As a result, this paper chooses the mainstream ESG rating system of A-share listed companies - CSI ESG rating data - as a proxy variable to measure the level of corporate ESG disclosure.

(4) Control variables: Referring to the studies of Xia. A (2023), Yang. S etc. (2023), the control variables in this paper mainly take the following factors into consideration: ① The number of years of listing (*Listage*): Ln (the current year year - the year of listing +1). ② Firm size (*Size*): the logarithm of the total assets of the firm at the end of the year. ③ Gearing ratio (*Lev*): total liabilities divided by total assets at the end of the period. ④ Equity concentration (*Top1*): the number of shares held by the first largest shareholder divided by the total number of shares. ⑤ Return on assets (*Roa*): net profit divided by ending assets. ⑥ asset turnover (*Ato*): operating income divided by the closing balance of total assets. ⑧ board size (*Board*): the number of board of directors. ⑨ level of economic development (*Ln GDP*): gross domestic product *per capita*. ⑩ industrial structure (*Struct*): secondary industry divided by gross regional product.

4.3 Sample selection and descriptive statistics

Considering the completeness, availability and timeliness of the data, this paper selects a total of 26,540 enterprises in China from 2009 to 2019 as samples for the study, and adopts the deletion method to clean the data from missing values and invalid values. All the data were obtained from China Statistical Yearbook, China Energy Statistical Yearbook and Wind database, Cathay Pacific database, etc. in previous years. In order to eliminate the effect of heteroskedasticity, this paper logarithmizes the variables with larger values before model estimation; at the same time, in order to avoid the effect of the magnitude on the regression coefficients, this paper

TABLE 1 Descriptive statistical analysis.

Variables	Sample size	Average	Median	Standard deviation	Minimum	Maximum
CEI	26540.00	0.08	0.08	0.09	−0.54	0.47
DID	26540.00	0.27	0.00	0.44	0.00	1.00
ESG	26540.00	0.73	0.73	0.05	0.37	0.93
Listage	26540.00	2.03	2.20	0.90	0.00	3.40
Size	26540.00	22.10	21.91	1.32	15.58	28.64
Lev	26540.00	0.43	0.42	0.21	0.01	1.70
Top1	26540.00	0.35	0.33	0.15	0.00	0.90
Roa	26540.00	0.04	0.04	0.08	−2.83	0.59
Ato	26540.00	0.63	0.52	0.54	−0.05	11.60
Board	26540.00	8.64	9.00	1.75	0.00	18.00
Ln GDP	26540.00	11.32	11.40	0.57	8.60	13.06
Struct	26540.00	42.70	44.20	11.00	11.70	89.80

standardizes the percentile ESG scores to the range of 0–1. Table 1 shows the descriptive statistics of all variables.

5 Empirical tests and analysis of results

5.1 Main effect analysis of carbon trading policy on carbon emission intensity

5.1.1 Benchmark regression analysis

This paper first examines the impact of carbon emissions trading pilot policy on the carbon emissions intensity of enterprises, and Table 2 summarizes the results of the benchmark regression. According to Model 1, the DID - policy time interaction term is the core explanatory variable of interest in this paper. The results show that the coefficient of the core explanatory variable *DID* is negative with or without control variables and passes the significance test at the 1% level. The absolute value of the correlation coefficients between the variables in general is less than 0.5, ruling out the problem of multicollinearity, and the result is in agreement with Li, Xian (K. Li et al., 2024; Xian et al., 2024) et al. However, some researchers have pointed out that the emission reduction effect of carbon trading policy is not significant, which may be caused by the sample differences between sub-sectors and regions (X. Feng et al., 2024b; G. Huang et al., 2015).

This paper provides the following interpretation of the results based on existing studies:s: from the perspective of the action pathway, China's carbon trading pilot policy focuses on reducing carbon intensity through technological innovation, industrial structure upgrading and improving resource allocation efficiency (C. J. Zhang et al., 2021); from the perspective of energy consumption and supply chain, carbon trading policy may indirectly affect carbon emission intensity of enterprises through influencing the consumption structure of the "consumption side" and the output scale of the "production side" (Wang et al., 2023); from the perspective of enterprise risk taking, carbon trading policy may make enterprises pay more attention to the downside risk of creditors risk premium requirements (Ni et al., 2022), but the establishment and operation of the emission rights trading market will bring positive expectations to participating enterprises that the level of corporate risk taking of participating enterprises will be significantly increased (Wang et al., 2023). However, the current carbon trading system still lacks macro-control and integrated supervision, resulting in a lack of flexibility in the adjustment of carbon price and carbon allowances, so some scholars hold the opposite view. According to (Kerr and Duscha, 2014), the uneven degree of marketization of the carbon market may cause market price distortion, reduce the efficiency of market resource allocation and lead to the overall cost of emission reduction; the rebound effect suggests that the "carbon rebound" caused by technological advances may undermine the effectiveness of incentives for innovation. Combining the regression results with the above analysis, with the promotion and improvement of carbon trading policy, the incentive-driven and cost-constraint effects of carbon trading policy can reduce the carbon emission intensity of pilot enterprises, and hypothesis 1 is valid. At the same time, according to the joint effect of environment and economy, carbon trading policy can improve the productivity and market competitiveness of enterprises through the paths of energy structure, technological innovation, industrial structure (Deryugina et al., 2021; F. Li et al., 2021) and cash flow (Chan et al., 2013; Duan et al., 2024), leading to the transformation of enterprises into a low-carbon economy.

As for the control variables, the impacts of the number of years of listing, enterprise scale, return on assets, and asset turnover on carbon emission intensity are positive, mainly because the expansion of financial scale and efficiency improvement are conducive to the growth of carbon emissions (H. Xu et al., 2023); while the industrial structure inhibits the carbon emission intensity, mainly because the industrial structure can significantly inhibit the carbon emissions through the change of factor allocation and technological change through the rationalization of industrial structure (Z. Li and Wang, 2022a); in addition, enterprise size, return on

TABLE 2 Benchmark regression results.

Variables	(1) *CEI*	(2) *CEI*
DID	−0.0157***	−0.0197***
	(0.00184)	(0.00147)
Listage		0.00260**
		(0.00122)
Size		0.0361***
		(0.00126)
Lev		0.00360
		(0.00448)
Top1		−0.00687
		(0.00695)
Roa		0.0289***
		(0.00817)
Ato		0.0376***
		(0.00414)
Board		0.000303
		(0.000388)
Ln GDP		0.00237
		(0.00217)
Struct		−0.000479***
		(0.000173)
Industry FE	Control	Control
Year FE	Control	Control
Constant	0.0800***	−0.724***
	(0.00117)	(0.0357)
Observations	26,540	26,540
R-squared	0.190	0.395
Number of id	3,462	3,462

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

assets, equity concentration, board size and economic development level do not affect carbon emission intensity.

5.1.2 Heterogeneity analysis

Due to the obvious differences in the economic, technological and social functions of enterprises of different ownership types, as well as *the level of digitization* of enterprises and the degree of inter-regional marketization, which have created imbalances in the level of economic development, resource endowment, and carbon emission reduction potentials, the effects of the policy implementation in pilot enterprises may vary. This paper will further explore the effects of enterprise ownership, degree of marketization, and digital transformation on the relationship between carbon trading pilots and the carbon emission intensity of enterprises, so as to further clarify the heterogeneity of the results of the role of carbon trading policies on carbon emission reduction of enterprises (Coad, 2007).,

(1) Heterogeneity of ownership categories

According to institutional theory, institutional pressure is an important driver of corporate carbon emission reduction (F. Wang et al., 2019). In China, the management of state-owned enterprises (SOEs) consists of government officials, and their assessment system focuses more on the implementation of government policies compared to corporate profitability (Yen and Abosag, 2016). Prior studies have shown regulatory discrimination between SOEs and non-SOEs(Yen and Abosag, 2016). The public generally expects SOEs to behave more in line with social preferences than private firms (Guan et al., 2021). Based on the social responsibility perspective and the "spotlight effect", large state-owned enterprises (SOEs), which dominate economic growth, employment, and social distribution, have unique social identities and reputations, and will be subject to greater pressure for organizational legitimacy (Liu et al., 2023); at the same time, the differences in business objectives and financing constraints between enterprises of different ownership systems make it inevitable for SOEs to assume more social responsibility (Wang, Ma, et al., 2023b). Based on the power allocation theory, information advantage (Bilal et al., 2022) and closer social network relationships (X. Chen, 2017) facilitate SOEs' access to government resources, and better business environment and financial efficiency make it easier for SOEs to enter the debt market and obtain (Herbohn et al., 2019) government subsidies (Lee et al., 2017). Based on the green innovation theory, imitation, norms and coercive pressure are important factors in the adoption of new technologies (Ma et al., 2023), while greater institutional pressure can help firms to realize process innovation and green products thus improving resource efficiency (Berrone et al., 2013). Therefore, state-owned enterprises are more likely to actively participate in carbon emission reduction than non-state-owned enterprises. This paper divides the sample into state-owned and non-state-owned parts and assigns the value of 1 to state-owned enterprises, otherwise 0. The results in Table 3 are consistent with the results of existing studies, i.e., state-owned enterprises are more conducive to strategic change and green governance due to their social nature and financing advantages.

(2) Heterogeneity of the degree of marketization.

Market-oriented reform plays an important role in optimizing the business environment and enhancing the vitality of enterprises' independent innovation (Cole and Elliott, 2003), and can improve the allocation efficiency of innovation resources by reducing the "crowding out effect" of government intervention, improving the mobility of factors and the enthusiasm for external financing (Hansen, 1999; Liu et al., 2020). At the same time, the diffusion of technology effects and the improvement of energy technology will further enhance the effectiveness of policies and the efficiency of enterprise carbon emission reduction (Flammer, 2018). Based on the perspective of social responsibility, the degree of marketization is positively correlated with the rule of law, the level of economic development and the degree of public concern, so the enterprises in

TABLE 3 Results of heterogeneity analysis.

Variables	(1) Isn't SOEs?	(2) Isn't high-market?	(3) Level of digitization
Heterogeneity	−0.00391*	−0.0255***	−0.000376***
	(0.00231)	(0.00218)	(0.000145)
DID	−0.0178***	−0.00586***	−0.0190***
	(0.00201)	(0.00204)	(0.000847)
Variables	0.00223*	−0.00118	9.18e-06-
	(0.00126)	(0.00741)	(0.000151)
Listage	0.0361***	0.00269**	0.00235***
	(0.00126)	(0.00120)	(0.000737)
Size	0.00348	0.0360***	0.0362***
	(0.00447)	(0.00125)	(0.000519)
Lev	−0.00645	0.00474	0.00343
	(0.00697)	(0.00444)	(0.00216)
Top1	0.0291***	−0.00736	−0.00674*
	(0.00816)	(0.00684)	(0.00347)
Roa	0.0375***	0.0295***	0.0289***
	(0.00413)	(0.00804)	(0.00306)
Ato	0.000302	0.0377***	0.0376***
	(0.000388)	(0.00407)	(0.000775)
Board	0.00222	0.000285	0.000322
	(0.00217)	(0.000387)	(0.000225)
Ln GDP	−0.000487***	0.00134	0.00229
	(0.000173)	(0.00218)	(0.00150)
Struct	−0.0178***	−0.000642***	−0.000468***
	(0.00201)	(0.000173)	(8.70e-05)
Industry FE	Control	Control	Control
Year FE	Control	Control	Control
Constant	−0.721***	−0.703***	−0.725***
Number of id	2,562	3,447	3,462

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

regions with a higher level of marketization are more prominent in the strength and effectiveness of their policy implementation (Krugman, 1991). In addition, the high marketization level of the region's market signal quality is higher, which is conducive to enterprises to a greater extent to avoid information asymmetry and obtain the optimal allocation of capital (Buera et al., 2011); market profit-seeking will lead to the flow of factor resources from the underdeveloped regions to the developed regions with high allocation efficiency, the formation of the "center - periphery pattern", exacerbating the heterogeneity of the effect of carbon emission reduction between regions (L. Chen et al., 2021). In summary, the uneven degree of marketization will lead to the heterogeneity of carbon emission intensity changes in different regions. According to the marketization index report, Shanghai, Zhejiang, Jiangsu, and Guangdong provinces are classified as high marketization regions, and the rest are low marketization regions. The results in Table 3 show that the emission reduction effect of carbon trading policy is affected by the degree of regional marketization: the degree of marketization plays a positive moderating role in the relationship between the role of carbon trading policy on carbon emission reduction of enterprises, and all of them are significant at the 1% level. This result is consistent with the results of existing studies, that is, the emission reduction effect of carbon trading is more significant in regions with higher levels of

TABLE 4 PSM-DID test results.

Variables	(1)	(2)
	CEI	*CEI*
DID	−0.00577***	−0.0102***
	(0.00162)	(0.00140)
Listage		−0.000584
		(0.00133)
Size		0.0381***
		(0.000913)
Lev		−0.00178
		(0.00389)
Top1		0.00511
		(0.00606)
Roa		0.0220***
		(0.00530)
Ato		0.0414***
		(0.00140)
Board		0.000522
		(0.000403)
Ln GDP		0.0133***
		(0.00330)
Struct		−0.000336**
		(0.000155)
Industry FE	Control	Control
Year FE	Control	Control
Constant	0.0869***	−0.882***
	(0.00169)	(0.0390)
Observations	10,174	10,174
R-squared	0.140	0.373
Number of id	2,898	2,898

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.
[a]Instrumental variables test.

TABLE 5 Results of Instrumental variables test and Lag test.

Variables	(1)	(2)
	CEI	*CEI*
Did_iv/Ldid	−0.124***	−0.0242***
	(0.0131)	(0.00141)
listage	0.00103	0.00302
	(0.000980)	(0.00210)
size	0.0380***	0.0358***
	(0.000717)	(0.00132)
lev	0.0160***	0.00504
	(0.00322)	(0.00474)
top1	−0.0185***	−0.00335
	(0.00476)	(0.00724)
roa	0.0346***	0.0289***
	(0.00406)	(0.00801)
ato	0.0416***	0.0361***
	(0.00113)	(0.00404)
board	0.000289	0.000303
	(0.000294)	(0.000404)
lngdp	0.00372*	−0.00357*
	(0.00196)	(0.00215)
struct	0.000640***	−0.000526***
	(0.000181)	(0.000180)
Constant	−0.831***	−0.667***
	(0.0283)	(0.0377)
Observations	26,540	22,856
Number of id	3,462	3,314

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

marketization, indicating that market-oriented reforms can effectively enhance the effectiveness of the policy and achieve the goal of low-carbon development (Wang et al., 2023; Yao et al., 2023).

(3) Heterogeneity of the level of digitization

As the digital economy continues to run at an accelerating pace, the level and development of digital technology in Chinese enterprises is constantly improving. Digital transformation has become an important strategic goal to promote the high-quality development of enterprises and an urgent need to address climate change in China. In the context of carbon trading policy, whether or not *the level of digitization* may cause heterogeneity of carbon reduction effectiveness among enterprises. Based on the green innovation perspective, the impact of the digital economy on enterprise-generated technology is divided into spillover effect and impact effect, which reduces enterprise costs while improving the overall operational efficiency of the company (Tian et al., 2024); at the same time, enterprises can increase the sharing of information in the carbon market through digitization to promote the development of green technology (Peng and Tao, 2022), and attract more financial support and government subsidies (Geng et al., 2023). Based on the theory of value creation, digital transformation can expand the scale of production and achieve economies of scale with high total factor productivity through paths such as reducing marginal production costs and optimizing labor factor allocation (Liu et al., 2023); at the same time, digital technology, as a tool for resource management, can reduce production time and maximize energy consumption (Awan et al., 2021). In addition, An and Zhang et al. demonstrated a

TABLE 6 Robustness regression results.

Variables	(1) Ln *CEQ*	(2) Ln *CEQ*
DID	−0.364***	−0.454***
	(0.0391)	(0.0303)
Listage		0.0193
		(0.0253)
Size		0.837***
		(0.0248)
Lev		0.0609
		(0.0900)
Top1		−0.135
		(0.141)
Roa		0.638***
		(0.170)
Ato		0.854***
		(0.0857)
Board		0.00508
		(0.00820)
Ln GDP		0.0401
		(0.0463)
Struct		−0.0111***
		(0.00356)
Industry FE	Control	Control
Year FE	Control	Control
Constant	1.721***	−16.66***
	(0.0249)	(0.725)
Observations	26,540	26,540
R-squared	0.210	0.440
Number of id	3,462	3,462

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.
[a]Placebo test.

positive correlation between the level of enterprise digitization and carbon emission reduction (An and Shi, 2023; W. Zhang et al., 2022). Referring to the approach of Qi et al. (Qi et al., 2020), this paper constructs a comprehensive measure of digital transformation by standardizing core enterprise technologies such as artificial intelligence, blockchain, cloud computing, and big data, as well as basic inputs such as digital capital, human resources, and infrastructure investment. The results in Table 3 show that *the level of digitization* plays a positive regulating role in the relationship between the role of carbon trading policy on carbon emission reduction of enterprises, and all of them are significant at the level of 1%, that is, the carbon trading policy has a greater impact on carbon emission intensity of high digitalized enterprise, which indicates that the digital transformation can effectively enhance the effectiveness of the policy.

5.1.3 Endogeneity tests

In order to ensure that the results are not affected by potential endogeneity issues, this study employs different methods to mitigate these issues, such as the propensity score matching method, the log-linear instrumental variables method, and the lagged change model.

5.1.3.1 PSM-DID

Policy implementation is by nature a non-randomized experiment, so the double-difference method used for policy effect assessment inevitably suffers from self-selection bias, whereas the use of the propensity score matching (PSM) method allows for each treatment group sample to be matched to a specific control group sample, making the quasi-natural experiment approximately randomized, and thus checking whether the results of the study are interfered with by the influence of other potential factors. For Hypothesis 1, in order to alleviate the endogeneity problem that may be caused by omitted variables, this paper uses the PSM-DID method to correct it. After the test, the coefficients of the explanatory variables are still significantly negative, and the coefficients of the remaining control variables are also in line with expectations, which indicates that the benchmark regression results remain robust when the selection bias problem is taken into account (e.g., Table 4).

5.1.3.2 Instrumental variables test

In order to address the endogeneity problem due to possible omitted variables and reverse causality, this paper draws on the research ideas of Hering et al. (Hering and Poncet, 2014), who used the Air Mobility Coefficient (ACR) to measure environmental policies. Specifically, cap-and-trade policies affect the rate of air pollution dispersion by controlling Greenhouse Gas (GHG) emissions, and thus the rate of air pollution dispersion. In the standard box model of air pollution, the ventilation coefficient is identified as a determinant of air pollution dispersion rate (Jacobson, 2002). Meanwhile, since the air mobility coefficient is determined by large-scale weather systems, it can be regarded as an exogenous characteristic of local economic activities (Jacobson, 2002; Yu et al., 2022). Therefore, in this section, the air mobility coefficient of the city where the sample firms are located is chosen as an instrumental variable, which is calculated as the product of unit wind speed and boundary layer height, and the relevant data are obtained from the China Meteorological Yearbook and provincial statistical yearbooks. The results in column (1) of Table 5 show that the estimated coefficient of the interaction term is still significantly negative. Therefore, after further mitigating the potential endogeneity problem, the carbon trading policy is still effective in reducing emissions.

5.1.3.3 Lag test

Since the impact of carbon trading policy on corporate carbon emission intensity may have a time lag, this study refers to the method of Si Pu (Pu and Ouyang, 2023), lagging all explanatory variables by one cycle and then re-evaluating the regression model. Column (2) of Table 5 shows that 1 year after the implementation of

carbon trading policy, the carbon emission reduction of enterprises is still significantly advanced.

5.1.4 Robustness tests

5.1.4.1 Replacement of explanatory variables

In this paper, the carbon emissions (*CEQ*) of enterprises are used to replace the explanatory variable carbon emissions intensity in the original model, as shown in Table 6. It is found that the sign and significance of the estimated coefficients of *DID* are basically consistent, which further supports the robustness of hypothesis 1.

5.1.4.2 Placebo test

In order to further test whether the impact of carbon trading policy on the carbon emission intensity of enterprises is generated by other unobservable factors, this paper conducts a placebo test by randomly assigning carbon trading pilots, and at the same time, in order to enhance the effectiveness of the placebo test, the above experimental process is repeated 500 times. The results are shown in Figure 2, the estimated coefficients are basically around the value of 0, and most of them are not significant at the 10% level, so the influence of other unobservable factors other than carbon trading policy on the empirical results can be excluded.

5.1.4.3 Parallel trend test

It is an important prerequisite for the use of the double-difference method that the experimental and control groups satisfy the parallel trend assumption, i.e., before the implementation of the carbon trading policy, the carbon emission intensity of each region maintains a relatively stable trend of change. Figure 3 shows the estimation results of the coefficient α and the corresponding 95% confidence intervals at different time points of the policy implementation. Before the implementation of the policy, there is no significant difference between the pilot regions and non-pilot regions. After the implementation of the policy, the carbon emission reduction effect is gradually and significantly negative, which satisfies the parallel trend hypothesis.

5.2 Analysis of regression results of ESG regulation effect

The basic framework of China's carbon emissions market was initially harmonized at the end of 2014; successively, the Hong Kong Stock Exchange upgraded the "recommended disclosure" to "explanation for non-compliance" in the ESG Guidelines in 2015, marking an increasingly mature policy environment. This paper will take 2015 as the cut-off point. In this paper, we will take 2015 as the cut-off point and use staged regression to explore the specific role effect of ESG disclosure level during the policy pilot period, and classify 2009–2015 as the pre-pilot period of the carbon trading policy and 2016–2019 as the post-pilot period of the policy. The model results show (Table 7) that the regression coefficient of the cross term in the pre-pilot period is 0.0380, while the coefficient in the post-pilot period is −0.0318, and both of them are significant at the 5% significance level, with a high degree of fit, which confirms the existence of the moderating effect of ESG disclosure level. For the sign difference of the coefficients in the stage before and after the pilot of the policy, this paper intends to explain as follows: the environmental and social responsibility information of Chinese enterprises has only entered the stage of combining voluntary disclosure and mandatory disclosure since 2008, and the maladaptation between the carbon trading policy and ESG disclosure mechanism will weaken the policy effect of carbon trading: the theory of overinvestment argues that ESG will increase the management cost of the enterprise and reduce the profit of the enterprise in the short term The theory of over-investment suggests that ESG will increase corporate management costs and reduce corporate profits in the short term, crowding out other productive investments and leading to

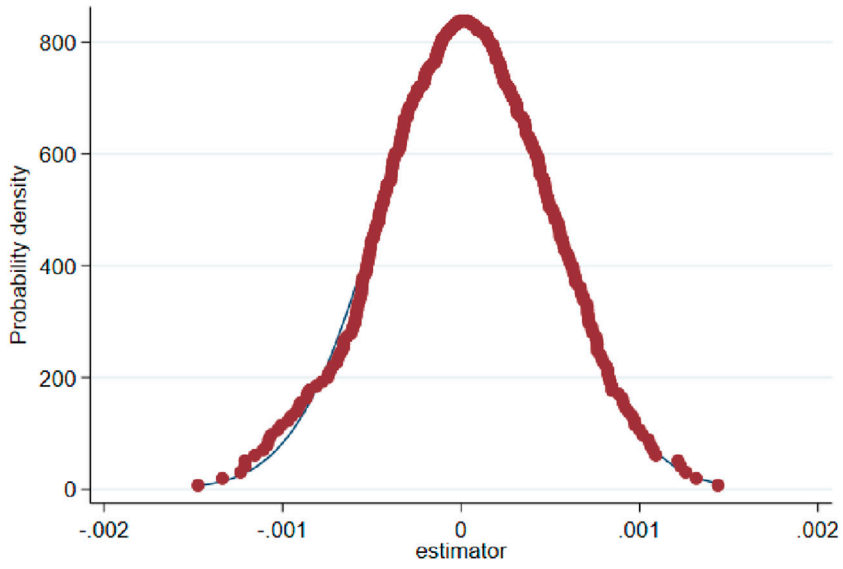


FIGURE 2
Placebo test.

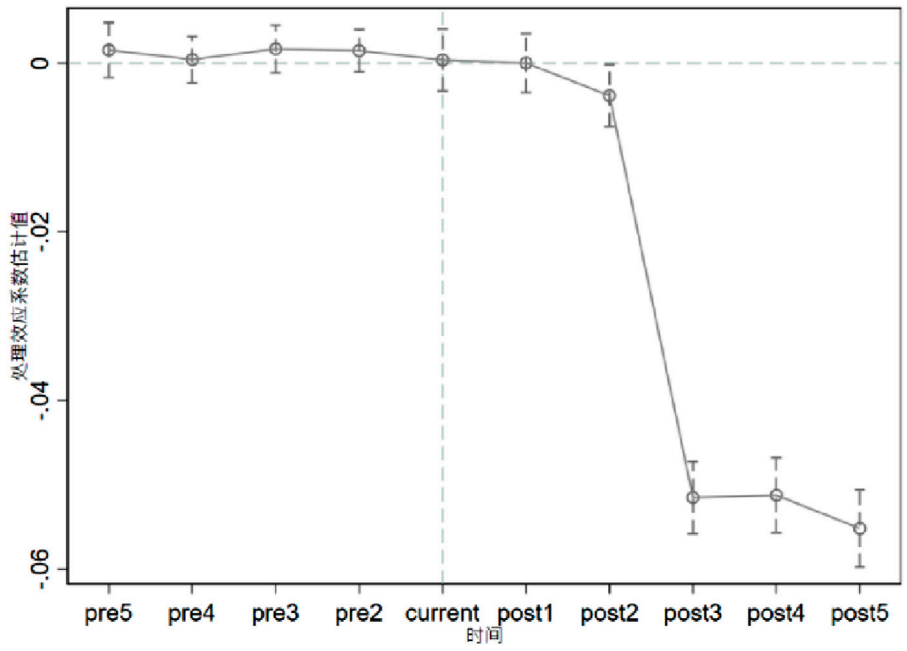


FIGURE 3
Parallel trend test.

a reduction in carbon productivity (Gao and Liu, 2023a) In addition, if the purpose of managers' behavior is not shareholder welfare, but self-interest, such as seeking to improve their personal reputation, the market for their trading will take a negative attitude (Bilyay-Erdogan et al., 2023). However, with the gradual improvement of ESG disclosure mechanism and carbon trading market, ESG disclosure level plays a positive moderating role in the carbon emission reduction effect of carbon trading policy: ESG can provide favorable conditions for the ecological construction of carbon trading market, avoiding the carbon hiding behavior of the companies with weak sustainability performance as much as possible. At the same time, ESG can improve the effectiveness of the policy and perfect the financing constraints by circumventing the asymmetry of information, improving the performance of corporate responsibility and innovation, and alleviating the financing constraints, thus promoting the carbon emission reduction effect of the carbon trading policy (Naeem et al., 2022). According to the legitimacy theory, a social contract will be established between the enterprise and the society, and the enterprise should act according to the beliefs, expectations, norms, standards, and values of the latter in order to achieve "legitimacy" and "social license to operate" (Gao and Liu, 2023b). Related research further confirms that the management of enterprises with ESG ratings is more likely to avoid the short-sighted behavior of only looking at immediate interests and pay more attention to the long-term development goals of enterprises, which is conducive to the green transformation of enterprises (Rahman et al., 2023). Summarizing the above analysis and empirical test results, ESG disclosure level weakens the policy effect in the early stage of carbon trading policy implementation, and positively moderates the degree of carbon trading policy's impact on carbon emission intensity in the later stage, and Hypothesis 2 is established.

In order to test the robustness of the results, this paper replaces the measurement of ESG disclosure level, drawing on Su Jingzeng's (Zeng et al., 2024) method of assigning values to ESG scores, and assigns the nine grades of C, CC, CCC, B, BB, BBB, A, AA and AAA of the composite results to be from 1 to 9, respectively, and the regression results are shown in columns (3) and (4), which do not change the original conclusions, so the original conclusions are robust. (*ESG* in the table is the percentage score of CSI ESG, and *ESG1* is the score of the assignment method.)

5.3 Spatial spillover analysis-moran index and SDM spatial durbin models

5.3.1 Spatial autocorrelation test

This paper introduces the geographic distance matrix to test the autocorrelation of the spatial panel data of carbon emission intensity, as shown in Table 8, except for 2016, which is not significant, the Moran' I of carbon emission intensity from 2009 to 2019 is significantly positive at the 10% level, indicating that the spatial and temporal distributions of the carbon intensity of China's 30 provinces are not completely random but This indicates that the spatial and temporal distribution of carbon emission intensity in the 30 provinces of China is not completely random, but there is a significant positive spatial correlation, i.e., the trend of the carbon emission intensity of each province and city will be affected by the carbon emission intensity of its neighboring provinces and cities.

5.3.2 Results of spatial spillover effects

Table 9 shows the results of the spatial spillover effect of the carbon trading policy on carbon emission intensity, and the

TABLE 7 Regression analysis of moderating effects.

Variables	(1) CEI	(2) CEI	(3) CEI	(4) CEI
Tiao Jie	0.0380***	−0.0318**	0.0176***	−0.0133*
	(0.0119)	(0.0155)	(0.00584)	(0.00743)
ESG/ESG1	0.000564	0.0138	2.04e-05	0.00501
	(0.00638)	(0.0100)	(0.00293)	(0.00486)
DID	−0.0297***	0.0517***	−0.00916***	0.0340***
	(0.00872)	(0.0119)	(0.00248)	(0.00443)
Listage	0.00518***	−0.00125	0.00517***	−0.00127
	(0.000805)	(0.00156)	(0.000805)	(0.00156)
Size	0.0354***	0.0383***	0.0355***	0.0383***
	(0.000652)	(0.00135)	(0.000651)	(0.00134)
Lev	0.0112***	0.00837*	0.0112***	0.00819*
	(0.00241)	(0.00445)	(0.00241)	(0.00444)
Top1	−0.00323	−0.00360	−0.00326	−0.00360
	(0.00398)	(0.00830)	(0.00398)	(0.00830)
Roa	0.0373***	0.0185***	0.0373***	0.0185***
	(0.00420)	(0.00405)	(0.00420)	(0.00405)
Ato	0.0356***	0.0320***	0.0356***	0.0320***
	(0.000950)	(0.00128)	(0.000950)	(0.00128)
Board	6.75e-05	0.00119***	6.62e-05	0.00119***
	(0.000236)	(0.000413)	(0.000236)	(0.000413)
Ln GDP	−0.0118***	−0.0337***	−0.0118***	−0.0337***
	(0.00124)	(0.00439)	(0.00124)	(0.00439)
Struct	0.000455***	−0.00159***	0.000455***	−0.00160***
	(0.000106)	(0.000140)	(0.000106)	(0.000140)
Industry FE	Control	Control	Control	Control
Year FE	Control	Control	Control	Control
Constant	−0.605***	−0.389***	−0.605***	−0.382***
	(0.0198)	(0.0561)	(0.0194)	(0.0559)
Observations	14,180	12,360	14180	12360
R-squared	0.327	0.375	0.327	0.375
Number of id	2,562	3,447	2,562	3,447

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

autocorrelation test is conducted on the spatial panel data of carbon emission intensity by constructing the geographic distance matrix as well. The spatial correlation coefficients ρ or λ of the three models are all significantly negative, and the estimates of *DID* are also significantly negative, indicating that there is a significant spatial spillover effect of the impact of the policy on carbon emission intensity. This paper further uses partial differential estimation to

TABLE 8 Statistical results of spatial autocorrelation test of carbon emission intensity.

Variables	*I*	*E(I)*	*sd(I)*	*z*	*p*-value*
s2009	0.045	−0.034	0.042	1.894	0.058
s2010	0.079	−0.034	0.043	2.627	0.009
s2011	0.058	−0.034	0.043	2.168	0.030
s2012	0.059	−0.034	0.042	2.213	0.027
s2013	0.064	−0.034	0.042	2.345	0.019
s2014	0.052	−0.034	0.042	2.076	0.038
s2015	0.052	−0.034	0.042	2.051	0.040
s2016	0.027	−0.034	0.041	1.496	0.135
s2017	0.073	−0.034	0.042	2.551	0.011
s2018	0.068	−0.034	0.042	2.413	0.016
s2019	0.070	−0.034	0.043	2.460	0.014

analyze the direct, indirect and total effects of the carbon trading pilot policy on carbon emission intensity. The regression results show that the indirect effect of the pilot carbon trading policy on carbon emission intensity is larger than the direct effect, indicating that the effect of the policy has a strong mobility between the pilot enterprises and the neighboring enterprises. In order to further enhance the credibility and accuracy of the conclusions, this paper uses the method of replacing the dependent variable, and after replacing the explanatory variable with the logarithm of the carbon emissions of the enterprises, the empirical results are basically the same in general, which indicates that the model has a certain degree of robustness. The result is in agreement with Lai, Dai et al. (Dai et al., 2022a; Lai and Chen, 2023a). However, some scholars hold the opposite view, possibly because under imperfect policies, productivity differences across firms may cause heterogeneity in carbon spillover outcomes (Lai and Chen, 2023b). Based on the empirical results, this paper analyzes the driving and inhibiting effects of carbon trading policies on carbon emission reduction from the perspective of spatial spillovers and the perspective of enterprises. The demonstration effect and competition effect among enterprises will encourage enterprises to develop new products or master new technologies, and force other enterprises to improve their productivity and competitiveness (S. Fazzari et al., 1987); meanwhile, Porter's hypothesis suggests that the "innovation compensation" effect brought by environmental regulation can offset the "compliance cost" of enterprises to a certain extent (L. Chen et al., 2023b). In this regard, the international academic community has put forward contradictory theories, such as Sinn's "green paradox hypothesis": in order to avoid the adverse impacts of environmental regulations, fossil energy producers will advance the extraction of fossil fuels, exacerbating climate deterioration (M. E. Porter and Linde, 1995b); and China's regional club effect: the presentation of the large enterprises *in situ* "green innovation", medium-sized enterprises "pollution transfer" of medium-sized enterprises, and closure of small enterprises. However, with the increase of pilot regions, the joint effect of environmental regulation can weaken the "green paradox"

TABLE 9 Results of spatial spillover effects.

Variables	*CEI*			*CEQ*		
	SEM	SAR	SDM	SEM	SAR	SDM
ρ or λ	−0.611***	−0.4912***	−0.7142***	−0.5931***	−0.4731***	−0.7398***
	(0.1533)	(0.1207)	(0.2561)	(0.1560)	(0.1224)	(0.2589)
DID	−0.0138***	−0.0131***	−0.0169***	−0.3152***	−0.2976***	−0.3886***
	(0.0044)	(0.0044)	(0.0046)	(0.0943)	(0.0939)	(0.0986)
*W1*DID*			−0.1046***			−2.5093***
			(0.0519)			(1.1142)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Direct effect		−0.0131***	−0.0145***		−0.2968***	−0.3296***
		(0.0045)	(0.0043)		(0.0973)	(0.09314)
Indirect effect		0.004***	−0.0581***		0.09656***	−1.3733***
		(0.0018)	(0.0318)		(0.0379)	(0.6770)
Total effect		−0.009***	−0.0725***		−0.2002***	−1.7029***
		(0.0030)	(0.0329)		(0.0664)	(0.7019)
Province	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
N	330	330	330	330	330	330
R^2	0.2030	0.2371	0.1531	0.2325	0.2620	0.1837

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

effect of individual environmental regulation variables (Dai et al., 2022b). At the same time, with the diversification of performance evaluation systems and the increase of environmental indicators, enterprises will gradually move from the "GDP only" mode of "bottom-up competition" to "bottom-up competition" mode of "GDP only." (Z. Zhang et al., 2020b). To summarize, the driving role in the spillover effect of carbon trading policy is dominant. In terms of economic benefits, China's gradient development model enhances spatial agglomeration effects and exhibits strong spatial dependence and convergence (G. Huang et al., 2015). However, interregional capital flows caused by carbon trading policies may increase the value and market competitiveness of neighboring firms through paths such as narrowing regional economic gaps, thus realizing Pareto optimality for the whole society (Fan et al., 2016).

6 Research conclusion

Starting from the perspective of enterprises, this paper uses a quasi-natural experiment based on the panel data of Chinese enterprises from 2009 to 2019, using the double-difference method, to comprehensively assess the impacts of carbon trading policies on carbon emission intensity in pilot and non-pilot regions, and to explore the mechanism role of ESG disclosure level in it. The research conclusions of this paper are as follows.

Carbon trading policy has an inhibitory effect on the carbon emission intensity of pilot enterprises, and there are significant differences under different scales and marketization degrees. Benchmark regression results show that the carbon trading policy has a significant negative effect on the carbon emission intensity of pilot enterprises, i.e., the carbon trading policy internalizes the externality problem to improve the level of green development of enterprises, optimize the industrial and energy structure, and mobilize the enthusiasm of enterprise management and stakeholders to achieve the combination of internal and external effectiveness, which promotes Pareto-optimality of the carbon market and achieves carbon emission reduction of enterprises. Heterogeneity analysis shows that the policy effect is more significant for state-owned enterprises, enterprises with a high degree of marketization and completed digital transformation, i.e., ownership type, the degree of marketization, and the digital transformation play a positive moderating role in the path of carbon trading policy on corporate carbon emission reduction.

In the pre-pilot stage of carbon trading, ESG disclosure plays a negative moderating role in the effect of carbon trading policy on the carbon emission intensity of enterprises; in the late stage of the pilot, ESG disclosure plays a positive moderating role in its path. The regression results of the moderating effect show that with the continuous improvement of ESG disclosure mechanism, the higher the level of corporate disclosure, the more it contributes to the carbon emission reduction benefits of carbon trading policy. That is, ESG disclosure can improve the effectiveness of carbon

trading policy by increasing the penetration rate of the carbon market, information transmission, and assisting in coordinated supervision, which indirectly strengthens its carbon emission reduction; it can also directly inhibit the source of corporate emission intensity by emphasizing the corporate social responsibility, enhancing the performance of green innovation, and alleviating the constraints of financing.

Carbon trading policy has an inhibiting effect on the carbon emission intensity of neighboring enterprises in the pilot areas, i.e., the knowledge and technology spillover and competition demonstration effect of the pilot areas of the carbon trading policy can drive the carbon emission reduction actions of neighboring enterprises, and change the competition from "competition at the bottom to competition at the top". The promotion of the policy and the enhancement of the mandatory attributes can weaken the "green paradox" effect, and the improvement of the monitoring system can effectively stop the "pollution transfer" and "free-rider" phenomenon.

As an early exploratory investigation, this study still has some limitations. In terms of data statistics, the carbon emissions of enterprises calculated through the emission coefficients may have systematic errors with the actual values. With the improvement of the database and the standardization of carbon measurement, scholars can make more accurate measurements on the enterprise panel. In terms of mechanism research, the link between the emission reduction effect of carbon trading policy and other corporate behaviors still needs to be further explored. In addition, this study only focuses on the practical effects of carbon trading policies in China, and thefuture research could focus on comparing the effectiveness of carbon trading policies in practice in different countries.

7 Policy recommendations

Based on the existing problems of carbon trading policy and ESG disclosure system as well as the above conclusions, this paper provides the government with the following concrete policy implementation suggestions based on the enterprise perspective.

(1) Optimize the design of carbon trading system and regulate the order of carbon market. In terms of carbon quota allocation, attention should be paid to the moderateness of regulatory intensity and the flexibility of carbon emission reduction target control; in terms of innovation compensation, carbon quota issuance policy should be combined with enterprise innovation incentives to enhance the efficiency of the government's environmental protection expenditures, reduce the burden on enterprises through financial subsidies and other welfare policies, and improve the quality of green innovation in non-state-owned small enterprises. In terms of social supervision, there are market failures in the operation of the current carbon market, such as discrete carbon market transactions, carbon price signal anomalies, etc. The corresponding legal system should be designed to address the financial attributes of the carbon market, improve the statistics, verification, and reporting system of corporate carbon emissions data, and establish well-organized and well-run trading platforms and third-party service institutions. In addition, the heterogeneity of the degree of marketization, the ownership type and the level of digitization of enterprises in each region should be fully considered for scientific decision-making: emphasize the importance of continuing to promote market-oriented reforms to ensure market liquidity and policy effects protect the rights of non-state-owned enterprises, and appropriately increase support for scientific and technological innovation, and give full play to the government's subsidies. Leverage; give full play to the role of demonstration and leadership of state-owned enterprises, and further enhance the awareness of social responsibility in the whole industry; increase support for enterprises' digital transformation and related technology research and development, and build a green and digitalized supply chain system.

(2) Improve the awareness of corporate disclosure and perfect the ESG evaluation and supervision system. Lack of awareness, lack of indicators, lack of supervision and other issues are important reasons that limit the development of ESG disclosure in China. In terms of disclosure awareness, the "market hand" and administrative means can be adopted to guide enterprises, such as through the issuance of green benefits, publicity of typical cases, improve the mandatory attributes of the policy, etc., to mobilize the enthusiasm of enterprise stakeholders; in addition, through the enhancement of the ESG investment awareness of the investment institutions, "forcing" enterprises to improve their information disclosure. In addition, by raising the awareness of ESG investment among investment institutions, enterprises can be "forced" to improve their information disclosure level. In terms of the indicator system, specialists from various industries should be trained to build a differentiated ESG disclosure framework system. In terms of supervision and management, the internal and external joint supervision model of "principal and government" can be adopted, and supporting policies for the supervision of third-party governance enterprises can be established.

(3) Strengthen the promotion of inter-regional carbon trading policies and build a synergistic corporate governance ecosystem. Based on the synergistic theory, we should give full play to China's institutional advantages, strengthen provincial and municipal coordination through top-level design and ensure implementation at the enterprise level, and strengthen the supervision of strategic interaction between local governments and enterprises, so as to avoid the "Pollution Paradise" caused by "bottomward competition". Avoiding the illusion of "pollution paradise" caused by "bottom-up competition". At the same time, the phenomenon of "closed-loop trading" indicates the lack of direct policy guidance and connection at the national level, so government intervention can be appropriately strengthened, and information-sharing platforms can also be set up to provide effective channels for exchanges and cooperation among enterprises. In addition, the demonstration and competition effects can be utilized to give play to the

government's role in recognizing and leading by example, setting up green certification awards for enterprises that take the initiative to reduce emissions, so as to promote the transformation of enterprise development strategies from "bottom-by-bottom competition" to "top-by-top competition".

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AH: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. TY: Conceptualization, Data curation, Writing–original draft. YK: Conceptualization, Writing–original draft. CL: Conceptualization, Writing–original draft. YL: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Selection and application of China environmental sustainability policy instrumental: a quantitative analysis based on "Dual Carbon" policy text

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The "Dual Carbon" policy is a strategic instrument for the realization of the "Dual Carbon"target. The quantitative analysis of the "Dual Carbon" policy can provide theoretical support and decision-making reference for the institutional design and adjustment of the policy, so as to further improve the "Dual Carbon" 1 + N policy system. By constructing a three-dimensional analysis framework of "instrument-goal-object", adopting the content analysis method, and combining the coding results of the "Dual Carbon" policy text to conduct multidimensional cross-analysis, we found that the overall design of the "Dual Carbon" policy is reasonable, but at the same time, there are problems such as unbalanced distribution of policy instruments, incomplete coverage of policy goals, insufficient synergy of policy objects, and low degree of matching between policy dimensions. In response to these problems, targeted mitigation measures are proposed.

KEYWORDS

environmental sustainability, "Dual Carbon" policy, quantitative analysis, policy instrument, policy goal, policy object

1 Introduction

Since the year 2006, China has been the world's largest emitter of carbon dioxide (Guan et al., 2021). China's CO_2 emissions grew 565 Mt in 2023 to reach 12.6 Gt. This represents an increase of 4.7%, as emissions from energy combustion increased 5.2% (IEA50,2024). China has actively implemented governance measures to mitigate climate change since the Paris Agreement (The Paris Agreement, 2015) came into effect in November 2016. China will increase its autonomous national contribution, adopt more aggressive policies and initiatives, and strive to achieve a peak in CO_2 emissions by 2030 and strive to achieve carbon neutrality by 2060 (herein referred to as "Dual Carbon"), General Secretary Xi J P stated at the 75th General Debate of the United Nations General Assembly on 22 September 2020. The promotion of China's economy's high-quality development is inherently reliant on the achievement of "Double Carbon" target. The decision to advance to a new stage in the development of economic society and energy technology is also inevitable (Jiang and Raza, 2023). China has constructed the "Dual Carbon 1 + N policy framework" as a timeline, roadmap and construction plan to achieve the "Dual Carbon" target, of which the"Opinions of the Central Committee of the Communist Party of China State Council on

the Complete and Accurate Implementation of the New Development Concept and the Good Work of Carbon Peaking and Carbon Neutrality" (hereinafter referred to as the "Opinions") is the top priority. The "Opinions" will serve as the top-level design, and will lead the formulation of a series of "Dual Carbon" policy, and on the basis of the existing "Dual Carbon" related policies, continuously extend the thickness, depth and breadth of the "Dual Carbon 1 + N policy framework". Although the basic structure of China's "Dual Carbon" 1 + N policy framework has been established (Lu, 2022), "Dual Carbon" encompasses a wide range of subjects, involves numerous fields, and will take place over the course of the next 3 decades or even longer. As a result, achieving the target of "Dual Carbon" is a multifaceted, lengthy, systematic project that calls for the Chinese government to continuously adjust, improve, and optimize the "Dual Carbon" policy. To enhance the stability and systemic nature of the "Dual Carbon" 1 + N policy framework and to identify the future "Dual Carbon" policy, it is crucial to understand the characteristics of the current layout, content, and structure of "Dual Carbon" policy and to analyze in depth which policy Instruments are used, what goal are achieved, and to whom these policies are applied. Finding the appropriate locations to execute future "Dual Carbon" regulations is also crucial. Based on this, this paper conducts a quantitative analysis of China's "Dual Carbon" policy, investigates their shortcomings, and suggests targeted relief countermeasures, with the goal of providing theoretical support for the quantitative analysis of China's "Dual Carbon" policy and other sides of policies and providing workable decision-making references for the design, adjustment, and improvement of China's "Dual Carbon" 1 + N policy framework.

2 Literature review

"Peak carbon dioxide emissions" refers to the peaking of CO_2 emissions, and "carbon neutrality" refers to the positive and negative offsetting of CO_2 emissions and removals, according to the UN Intergovernmental Panel on Climate Change (IPCC) report and the worldwide consensus (IPCC, 2018; Wei et al., 2018; Zou et al., 2021). The term "Dual Carbon" has gained significant attention from academics both domestically and internationally. It has also become a major topic of global concern. At this time, the majority of academic study on "Dual Carbon" is concerned with the advancement of technology, evaluation of its impacts, realization pathways, and advancement in practice. Nature examines many suggestions for how China could achieve neutrality before 2060 from significant research organizations that collaborate closely with the government. According to the two research groups, China must first start generating the majority of its electricity from emission-free sources, and then increase the usage of this clean energy wherever it is practical, such as by converting from gasoline-powered cars to electric ones (Mallapaty, 2020). Xiao et al. discussed the importance of AI technology in achieving carbon neutrality in the shipping industry (Xiao et al., 2024). Williams J. H. et al. Developed a roadmap for achieving deep decarbonization in the United States by modeling the energy and industrial systems of the country, simulating in detail the transition paths in a number of industries, including construction, electricity, transportation, and industry. According to research, the United States may attain zero emissions without changing its behavior by gradually increasing energy efficiency, switching to electrical technology, utilizing clean electricity (particularly wind and solar), and installing a tiny quantity of carbon capture equipment (Williams, 2021). By De La et al. Four ET scenarios are created using the Kaya Identity and "gradual" or "rapid" narratives, using Mexico as an example. The findings demonstrate that adhering to RTS moves Mexico one step closer to becoming carbon neutral. A number of tactics are suggested, such as lowering the carbon intensity of the energy supply mix, raising energy efficiency, giving environmental protection top priority, improving activities based on science, and fostering environmental education and awareness (De et al., 2022). Koondhar et al. found that bioenergy consumption could help achieve carbon neutrality (Koondhar et al., 2021). Lee et al. proposed a creative method of waste gasification treatment that could help achieve carbon-neutral cities (Lee et al., 2021). Safi et al. assessed using panel data econometric techniques and found that environmental taxes、credit financing、antitrust exemption and shipping alliances can contribute to achieving carbon neutrality targets in economies (Safi et al., 2021; Xu et al., 2024; Xiao et al., 2024). Abbasi showed that natural resource depletion can provide a significant stimulus to CO_2 emissions in the short term through dynamic autoregressive distributed lag (ARDL) models and robustness checks (Abbasi et al., 2021).

Scholars have also performed some research on"Dual Carbon" policy from various angles and using varied methods. Oh et al. contend that Korea's ability to meet its 2050 carbon neutrality goal will depend on the effectiveness of carbon pricing measures in attracting private climate finance (Oh et al., 2021). Dahal et al. study renewable energy policies using a multilevel perspective (MLP) and semi-structured interviews, and argue that the implementation of renewable energy policies is a key component in achieving carbon neutrality target (Dahal et al., 2018). Hussain et al. constructed a mathematical model of the duo-oligopoly game, and after analyzing various carbon neutral policies, they pointed out that green bonds, carbon taxes, carbon emission allowances, and capacity-sharing modes play a crucial role in carbon neutralization (Hussain and Lee, 2022; Xu et al., 2022). Huang R et al. based on the extended STIRPAT model and LEAP-Beijing model, this paper assesses the key areas and pathways for carbon emissions reduction in Beijing for the period of 2015–2060 under six different policy scenarios. The results show that energy structure upgrading and energy efficiency improvement are the key drivers for the city's emissions reduction (Huang et al., 2022). Chen et al. quantify the Arctic oil spill event impact with an ensemble framework supported by the analytic network process (ANP) and fuzzy comprehensive evaluation model. The proposed framework provides a novel and reasonable decision-making instrument, which can contribute to the achievement of carbon neutrality in the marine environment (Chen et al., 2022).

Compared with the research on "Dual Carbon" practice and technology, there is still a lack of research on "Dual Carbon" policy, and there is the following room for expansion in the current policy research: First, from the perspective of research methodology, the majority of the current studies are qualitative, concentrating on macro-level and theoretical discussions, while a small number of

TABLE 1 Summary of "Dual Carbon" policy texts (excerpt).

Number	Policy name	Regulatory authority	Date of issue
1	Higher Education Carbon Neutral Science and Technology Innovation Action Plan	Ministry of Education of the People's Republic of China	2021.7.12
2	Standardized Energy Peak Carbon Neutral Upgrading Action Plan	National Energy Administration	2022.9.20
...	...	...	...
176	Implementation Program for Peak Carbon Achievement in the Industrial Sector of the Tibet Autonomous Region	Department of Economy and Informatization of the Tibet Autonomous Region	2023.5.8

quantitative studies concentrate on the creation of policy models and the evaluation of the effects. The quantitative study of policy texts, in particular, primarily uses a one-dimensional or two-dimensional analytical framework. Second, the number of samples used in present studies' quantitative analyses, which use a single policy text as a sample, needs to be increased from the viewpoint of research objectives.

Therefore, this study uses China's "Dual Carbon" policy as its research subject, employs the content analysis method, builds a three-dimensional framework for policy analysis called "instrument-goal-object" and evaluates the "Dual Carbon" policy released by China's national and provincial governments. Theoretical support for the quantitative study of "Dual Carbon" policy and other sides of policies may be obtained from the quantitative study of "Dual Carbon" policy, which can also serve as a foundation for the best institutional design of China's "Dual Carbon"policy. At the same time, it can serve as a significant source of decision-making guidance and practical inspiration for China's "Dual Carbon" policy, helping to further enhance the "Dual Carbon" 1 + N policy framework".

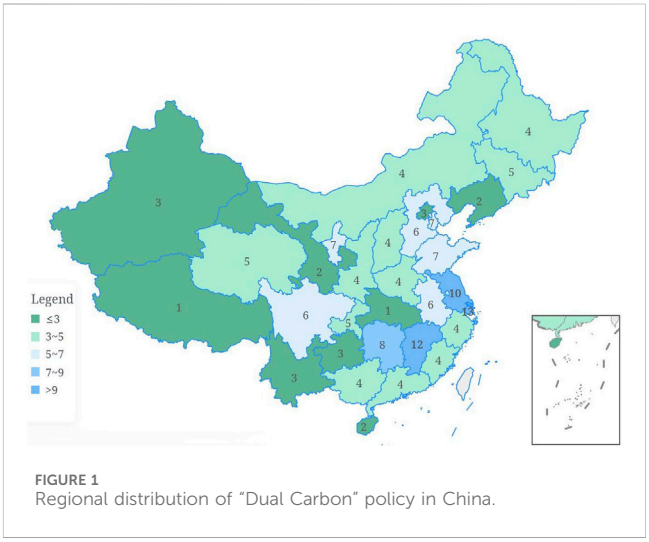


FIGURE 1
Regional distribution of "Dual Carbon" policy in China.

3 Materials and methods

3.1 Sample selection

Firstly, the policy texts were selected. The sources of the policy texts are the magic weapon of Peking University, Wan fang database, as well as Chinese government website, General Office of the State Council of the People's Republic of China, official websites of ministries and commissions (e.g., Ministry of Education of the People's Republic of China, Ministry of Finance of the People's Republic of China, etc.), and provincial local government websites. Republic of China, etc.) and provincial local government portals (e.g., The People's Government of Beijing Municipality, Shanghai Municipal People's Government, etc.). Search by full text, the keywords used were "Dual Carbon", "Carbon Neutrality", and "Carbon Peaking"; the policy text collection time was set from 30 September2020, to 31 December2023, with the announcement of the "Dual Carbon" targets as the starting point. Secondly, to ensure the authority, credibility, and representativeness of the selected policy texts, this study adhered to the following principles: (1) Policy texts are officially published opinions, decisions, notifications, plans, work plans, management measures, outlines, etc.; (2) Policy content is closely related to the "Dual Carbon"field; (3) Policy texts clearly state that achieving "Dual Carbon" targets is the policy orientation; (4) Only the latest versions of the same category of policies currently in effect were selected. Finally, according to the above standards and the principle of maximum effort sampling, 176 policy texts were ultimately screened (Table 1), including 23 central "Dual Carbon"policy texts and152 provincial "Dual Carbon"policy texts, covering relevant policies issued by 31 provincial administrative regions excluding Hong Kong, Macao, and Taiwan. The policy texts were numbered one by one in sequence by first central then regional (administrative region codes ascending) and release time (from earliest to latest) to construct a database of China's "Dual Carbon"policy texts, which serves as the foundation for quantitative analysis of policy texts. The regional distribution statistics of "Dual Carbon"policies show that more policies have been released in regions like Shanghai, Jiangxi, Jiangsu, and Hunan (Figure 1).

3.2 Construction of "instrument-goal-object" framework

Policy is the process of designing, selecting, and applying various policy instruments by governments. Policy instruments have clear objectives and operational guidance, and the policy instrument dimension focuses on the specific means utilized by the government in the policy process, involving the effectiveness of policy formulation and the operability of policy implementation.

Operable policy instruments can help the government guide the development of relevant industries and fields more clearly, to realize the policy goals (Furlan et al., 2018). However, policy instruments cannot characterize the elements or content of policies, and policy analysis based on a single dimension of policy instruments will lead to an incomplete policy analysis. (Yi and Feiock, 2014). To better reflect the means adopted by policies, the process of goal realization, as well as the inherent laws and characteristics of policies, this paper introduces the dimensions of policy goals and policy objects, which are useful to complement the single perspective of policy instruments. The policy goal dimension focuses on the specific goals established in the process of policy formulation and the desired realization effects. Policy goals should be closely related to policy instruments and have clarity to facilitate the assessment of the effectiveness of policy implementation. The policy object dimension focuses on the subjects, industries, and fields targeted by the policy. In the process of policy formulation, the policy object will change according to the different policy goals, and the government needs to choose the appropriate policy object according to the actual situation (Huang et al., 2020). The framework has the following characteristics: (1) Systematic. It can systematically integrate the core elements of the policy process. By focusing on the three key dimensions of policy instruments, goals, and objects, the policy background, formulation process, and implementation effectiveness can be analyzed comprehensively, thus avoiding the one-sidedness caused by research based solely on policy instruments. (2) Coherence. Policy formulation, implementation, and evaluation can be linked together, helping to analyze the interconnections and roles between policies at different stages. By tracking the selection of instruments, target setting, and object positioning of policies in the formulation process, and examining the actual application and impact of these elements in the policy implementation and execution stages, it is possible to more accurately assess the effects of policies, and further understand the completeness and consistency of the policy system. (3) Operationalization. Enables policymakers and practitioners to identify the relationship between policy instruments, goals, and objects, to introduce targeted policy measures, and improve the enforceability, effectiveness, and relevance of policies. (4) Insight ability. Provides policy research with a method for comprehensively sorting out and analyzing policy elements, thus helping to dig deeper into the internal laws and characteristics of policy formulation and implementation. Utilizing this framework, it is possible to better interpret the intentions, policy orientations, and practical effects behind policies, thereby providing insightful views and suggestions for policy improvement and innovation.

3.2.1 Dimension X: policy instrument

The many methods and instruments that governments use to accomplish their goals in terms of public policy are known as policy instruments (Howlett, 1991). The innovation and optimization of policy Instruments can improve the practice of public management, but the premise is to define the sides of policy instruments in a reasonable way (Li and Gu, 2016). McDonnell et al. divide them into four categories: systemic transformation, capacity building, inducing and motivating, and empowering and commanding (McDonnell and Elmore, 1987). Schneider et al. based on the goals of the policy, divide them into five categories: learning, capacity building, authority, motivation, and exhortation (Schneider, 1990). Howlett et al. classify them into three categories: mandatory, mixed, and voluntary, based on the degree of policy intervention (Howlett et al., 1995). Hughes et al. classified government functions into four categories: government supply, production, subsidy, and regulation (Hughes, 2017). The most representative of these is Rothwell and Zegveld's classification of supply-side, demand-side, and environment-side (Rothwell and Zegveld, 1984). Rothwell and Zegveld's classification of policy instruments has a more systematic and comprehensive policy analysis viewpoint (Hu et al., 2019), which is relevant given the broad variety of topics covered by "Dual Carbon" policy. Therefore, in order to assess the X dimension of China's "Dual Carbon" policy, this research utilizes Rothwell and Zegveld's classification of policy instruments. This study defines the sides of policy instruments from the supply, environment, and demand levels, which are grouped into 12 policy instruments (Table 2).

Supply-side refer to the top-down method used by the government to actively influence "Dual Carbon" related domains or links, including talent training, financial support, infrastructure, and information services. The environment-side policy instruments refers to the institutional framework that the government has established to support the development, implementation, monitoring, and direction of"Dual Carbon"policy, including target planning, regulatory control, advocacy guidance, and tax benefits. Demand-side policy instruments, which include government purchases, strategy measures, cooperation and outsourcing, and market control, refer to the efforts made by the government to lessen opposition to the carbon market and boost the vitality of carbon market participants. To achieve the"Dual Carbon"target, multiple policy instruments will interact with one another (Figure 2).

3.2.2 Dimension Y: policy goal

The desired consequences of policy formulation and implementation, as well as the underlying assumptions and standards for policy implementation and evaluation, define the scope of the decision-making process when choosing policy goals Wang et al. discovered that policy goals are the topics that need to be focused on in the current research on China's "Dual Carbon" policy through the research on the boundaries of China's "Dual Carbon" policy. To analyze "Dual Carbon" policy, policy objects are used as the Y dimension in this paper. The "Dual Carbon" target encourage high-quality development that strikes a balance between the benefits to the environment and the economy and seeks to accomplish a thorough ecological, economic, and social green transformation. Based on the above discussion, The ecological, economic, and social green transitions are viewed as the specific evolution and sub-target of the "double carbon" strategic goal based on this and the main layout of the opinions (Table 3).

3.2.3 Dimension Z: policy object

Different policy objects have different behavioral characteristics, rights, and responsibilities, which interact with one another in various policy stages, areas, and links and are the requirement and cornerstone for achieving policy functions. Policy objects are the target groups of policy implementation. As a result, the primary element used to describe the policy's attributes is the policy object. The government, businesses and organizations, and the general people are referred to in this paper as the Z dimensions of the

TABLE 2 Sides, names, descriptions and sources of policy instruments.

Sides	Name	Description
Supply-side	Talent training	Promoting "Dual Carbon"education and training and building a talent pool (De, 2021)
	Financial support	Direct government funding in the form of different financial grants and specialized subsidies (Kang, 2019)
	Infrastructure	To ensure the smooth implementation of energy saving and emission reduction activities in urban and rural areas improve various infrastructure and services (Li et al., 2021; Ma et al., 2021)
	Information services	Government publishes technical guidelines, standards and other information related to "Dual Carbon" (Hu et al., 2020)
Environmental-side	Target planning	Overall planning and requirements to achieve the "Dual Carbon" target (Liao, 2016; Hu et al., 2021)
	Regulatory controls	supervising and controlling diverse topics' activity in accordance with rules and regulations (Li et al., 2023)
	Advocacy guidance	Encourage everyone to be environmentally conscious and to reduce their carbon footprint (Xie et al., 2021)
	Tax benefits	The government offers tax breaks to businesses, organizations, and people who accomplish "Dual Carbon" in certain industries (Li et al., 2021)
Demand-side	Government purchases	Government spending programs intended to achieve the "double carbon" target (Yue et al., 2020)
	Strategy measures	To achieve the "Dual Carbon" target, there are incentives and disincentives at all levels of government, sectors, and industry (Ma et al., 2019; Meng and Wang, 2022)
	Cooperation and outsourcing	Sharing of expertise, collaboration in scientific research, outsourcing of services, etc. Between multiple organizations (Meng and Wang, 2022)
	Market control	Enhance the market system and encourage everyone to take an active role in energy conservation and emission reduction efforts (Zhang and Liu, 2016)

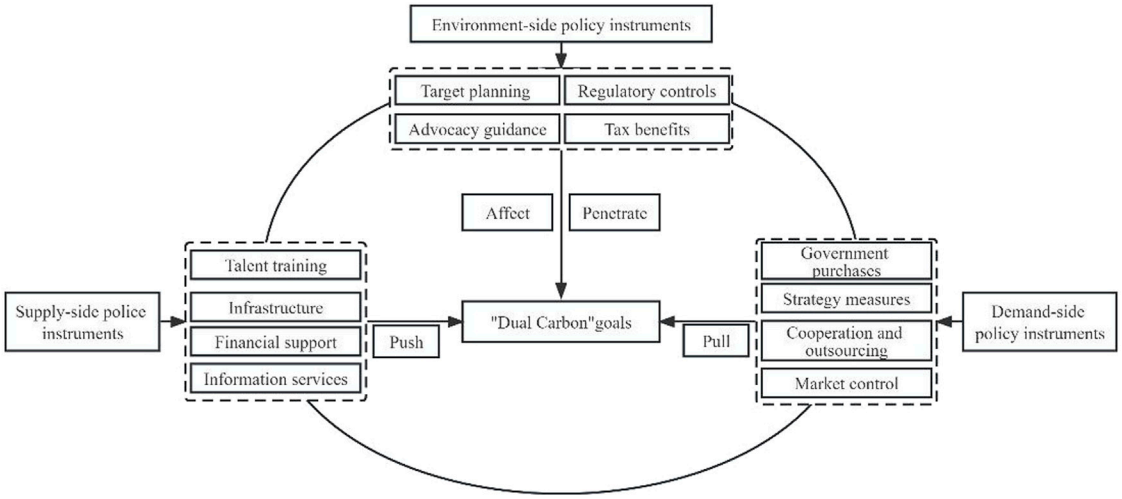


FIGURE 2
Interaction between policy instruments.

TABLE 3 Policy goals and descriptions.

Policy goal	Descriptions
Ecological green transition	boost carbon sinks, strengthen ecological and environmental management, and promote green ecology
Economic green transition	Establish a green industrial system, carry out green manufacturing initiatives, enhance green development mechanisms, and create a green, low-carbon, and circular development economic system
Social green transition	creating a culture of environmentally friendly living, awareness of low-carbon consumption, and green travel

TABLE 4 Policy objects and descriptions.

Policy object	Descriptions
The government	The central government, ministries, local governments, and line ministries at the provincial level are the objects of the policy
Businesses and organizations	The policy is intended for use by businesses, public organizations, nonprofit organizations, etc
The public	The public is the object of the policy

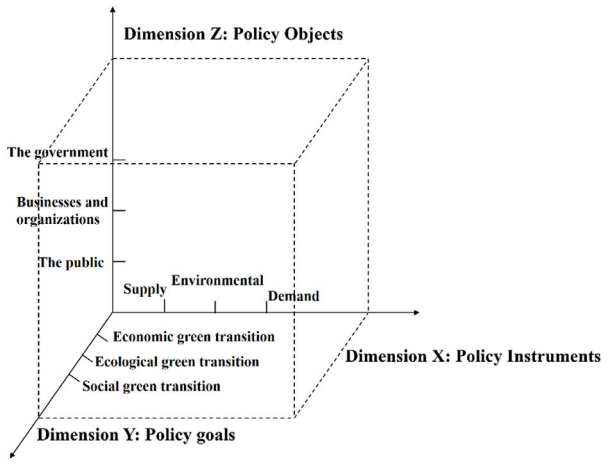


FIGURE 3
Three-dimensional framework for analysis of "Dual Carbon" policy.

"Dual Carbon" policy analysis framework, which was based on research by Zhang (Zhang et al., 2021) (Table 4).

By merging the three dimensions of the "instrument-goal-object" of the policy, a three-dimensional analysis framework of the "Dual Carbon" policy is created based on the analysis and description provided above (Figure 3).

3.3 Coding process

3.3.1 Coding classification

The first step was to divide the policy texts down into policy clauses, which served as the smallest unit of analysis. Clauses that did not pertain to the article's subject were eliminated, and the remaining clauses were coded with "policy number - order of policy clauses"; The second step was to carefully examine the policy's texts and create a preliminary summary of the provisions' contents. Finally, the policy clauses were categorized into various coding categories to form a complete policy coding framework. The same policy provision may use multiple policy instruments simultaneously, fail to display the goal or object; or achieve multiple objectives concurrently, act on multiple objects concurrently, etc., so that some policy provisions may not cover all dimensions but all cover X dimensions (Table 5).

3.3.2 Reliability and validity testing

This study conducted a reliability test to ensure sure the coding was of high quality and to strengthen the scientific rigor of the policy texts analysis. According to the coding consistency formula established by Viney: E = 4C/(n1 + n2 + n3 + n4) (Viney, 1983), four academics who are familiar with the "Dual Carbon" target and have a high coding foundation were first permitted to carry out the independent coding checking system. Where n1, n2, n3, and n4 are the number of codes produced by each coder and C is the total number of coders producing the same number of codes. When E [0.8, 0.9] shows that the confidence result is adequate, and when a >0.9 shows strong confidence. The coding results in this research are believable because the confidence value of the results is 0. 84 after calculation. In this study, the policy samples were chosen by conducting a text search and screening against the ten key elements of the "Opinions" actions. At the same time, the policy texts were supplemented and gathered in Baidu and other search engines by grouping the names of the central government, ministries, and commissions, as well as the names of the party and government leader agencies in each province, with the search terms. In order to guarantee the accuracy of the policy assessments, the policy texts were also reverse-engineered in terms of the links between policies' inheritance and citation.

4 Empirical analysis

4.1 One-dimensional linear analysis

4.1.1 Analysis of X dimensional results

In terms of the X dimension (Figure 4), the "Dual Carbon" policy texts use a variety of supply-side, environment-side, and demand-side policy instruments, they are often characterized by strong supply, light environment, and weak demand. Nearly half of them (43.52%) fall within the supply-side category, with the environment coming in second (35.82%) and demand-side (20.67%) falling in third. Financial support (64.14%) is the largest supply-side policy instrument; target planning (33.1%), publicity and guidance (28.28%), and regulation and control (27.01%) are the largest environment-side instrument; market control (37.45%) and government purchases (36.85%) are the largest demand-side instrument. As can be shown, the following characteristics best describe the distribution of policy instrument dimensions: (1) Tax incentives are underemphasized among environmental policy instruments, accounting for only 4.16% of all policy instruments. (2) Tax incentives are underemphasized among supply-side policy instruments, accounting for more than twice as much as demand-side ones. (3) The pulling effect of demand-side policy instruments is weak, with policy synergy (1.93%) accounting for the smallest share of all policy instruments. (4) There is an imbalance in distribution within policy instruments, and a sizable gap between supply and demand. Fourthly, the usage of a single policy

TABLE 5 Example of policy texts coding.

Texts analysis unit	Summarization	Coding categories		
		Instruments	Goals	Objects
To ensure that the primary objectives, development directions, major policies, and major projects for the implementation of carbon peaking and carbon neutrality are coordinated across all regions and areas, strengthen the interaction and coordination between various planning levels	All levels of government have to coordinate their policies	Strategy measures	Ecological green transition	The Government
Encourage sustainable, low-carbon lifestyle and resource efficiency. Encourage the reuse of mulch and the intelligent use of livestock manure and crop straw	Encourage and direct low-carbon and cost-effective agricultural production technologies	Advocacy guidance	Social green transition	The public
standardize the green design's construction. For greening projects that receive financial support, the construction unit is responsible for creating an operational design (also known as a greening program), and the department in charge of the project collaborates with other departments as needed to assess the operational design's logic in terms of land use, water use, and technical measures, as well as to oversee its implementation	Demand that the relevant government departments supervise and coordinate business activity related to the green economy	Regulatory controls	Economic green transition	The Government Businesses and organizations

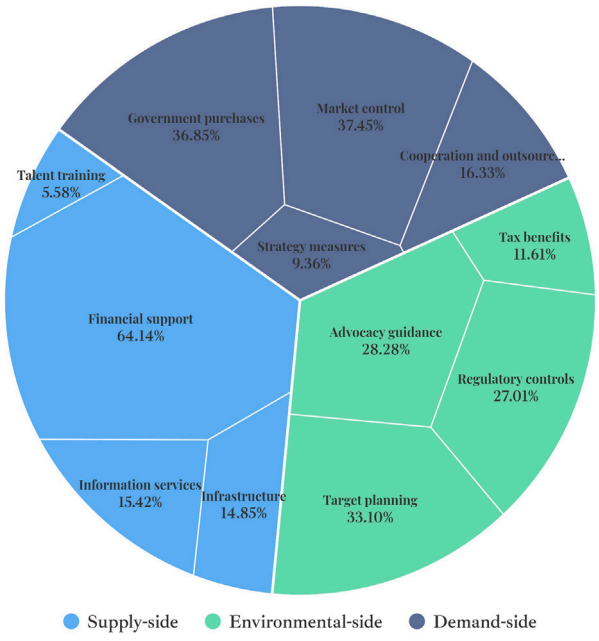


FIGURE 4
Distribution of "Dual Carbon" policy goals.

TABLE 6 Distribution of "Dual Carbon" policy goals.

Policy goals	Amount	Overall percentage (%)
Ecological green transition	1,408	61.08
Economic green transition	588	25.51
Social green transition	309	13.41
Total	2,305	

TABLE 7 Distribution of "Dual Carbon" policy objects.

Policy object	Amount	Overall percentage (%)
The government	1,199	53.72
Businesses and organizations	814	36.47
The public	219	9.81
Total	2,232	

instrument is excessive, and the distribution within each policy instrument is unbalanced, talent training is more than ten times more expensive than financial support.

4.1.2 Analysis of Y dimensional results

In terms of the Y dimension (Table 6), the ecological green transformation goals (61.08%) are the most widely distributed, followed by the economic green transformation goals (25.51%), and the social green transformation goals (13.41%) are relatively less widely distributed, with the distribution of the three sides of policy goals being roughly 4.5:1.9:1. This shows that the current emphasis on the social green transformation goals is inadequate. When formulating policies, attention should be paid to the comprehensive promotion of several objectives.

4.1.3 Analysis of Z dimensional results

In terms of the Z dimension (Table 7), the government, businesses and organizations, and the general public account for 53.72%, 36.47%, and 9.81%, respectively. This accurately reflects the government's dominant role in the process of achieving the "double carbon" target as the policymaker, overseer, and implementer, acting in a macro-guidance role. However, businesses, organizations, and

TABLE 8 Distribution of policy instruments used for "Dual Carbon" goals.

Goals instruments	Ecological green transition	Economic green transition	Social green transition	Subtotal	Total
Talent training	30	20	6	56	Supply-side (1,002)
Financial support	430	198	40	668	
Infrastructure	66	38	28	132	
Information services	80	51	15	146	
Target planning	158	50	73	281	Environmental-side (818)
Regulatory controls	129	52	42	223	
Advocacy guidance	127	43	50	220	
Tax benefits	37	39	18	94	
Market control	120	49	9	178	Demand -side (485)
Government purchases	158	9	16	183	
Strategy measures	34	8	3	45	
Cooperation and outsourcing	39	31	9	79	
Total	1,408	588	309	2,305	
percentage	61.08%	25.51%	13.41%	100%	

the general public are also important factors in achieving the "double carbon" target, so it is crucial to develop and enhance the participation mechanism to encourage and direct all different sides of subjects to actively participate in the process of achieving the "double carbon" target.

4.2 Two-dimensional cross-tabulation analysis

4.2.1 Analysis of X-Y dimensional results

Cross-tabulation analysis of the X-Y dimensions was carried out (Table 8). A total of 2,429 items made up the overall X dimension, whereas 2,305 items made up the cross-coding with the X-Y dimension, showing the existence of numerous policy instruments working on the same goal.

Cross-sectionally, supply-side policy instruments (43.47%) were most effective in achieving the policy goals, followed by environmental-side policy instruments (35.49%) and demand-side policy instruments (21.04%). The three sides of policy instruments that were used the most frequently were financial support, target planning, and government purchases, showing that the government favors promoting the "double carbon" target through various special or green project subsidies, important pilot projects, and regulations.

Cross-vertically, the frequency of ecological transition, economic green transition, and social green transition are 408, 588, and 309, respectively. Figure 3 shows that the government primarily supports the achievement of ecological and economic green transition goals by providing resources like talent, information, and infrastructure; social green transition goals, on the other hand, use more target planning, regulatory controls, and advocacy guidance policy instruments, showing that the government primarily creates awareness of energy conservation and emission reduction in the entire society.

4.2.2 Analysis of X-Z dimension results

Cross-tabulation analysis of the X-Z dimensions was carried out (Table 9). A total of 2,429 items made up the overall X dimension, whereas 2,232 items made up the cross-coding with the X-Z dimension, suggesting there may be several-side acting on the same object.

Cross-sectionally, the majority of instruments employed in supply-side (44.09%) are financial support, infrastructure, and information services, with talent training being utilized much less frequently than other instruments (and at a much lower rate overall); A moderate amount of environmental-side (34.77%) are used, with a use ratio of 3.3:1 and a significant difference between target planning and tax benefits. Demand-side (21.15%) made up the smallest percentage, in which market control and government purchases were closely tracked. This shows how highly the government regarded the resource and energy market trading system, as well as green pilots and important initiatives.

Cross-vertically, the most common sides of policies used by businesses, governments, and other organizations are supply-side, followed by environment-side and demand-side. Of the policy sides that are directed at the general public, environment-side account for the largest share (984), while supply-side and demand-side strategies account for the next largest shares (776) and 472, respectively. This is consistent with the roles played by governments, businesses, organizations, and the general public in achieving the "Dual Carbon" target: the government, as the main decision-maker, primarily offers ideological and practical guidance on policy-making, technological research and development, public awareness, etc., but it is also the primary source of carbon

TABLE 9 Distribution of policy instruments used by "Dual Carbon" policy objects.

Objects instruments	The government	Businesses and organizations	The public	Subtotal	Total
Talent training	22	30	1	53	Supply-side (984)
Financial support	330	310	21	661	
Infrastructure	56	49	21	126	
Information services	58	78	8	144	
Target planning	168	78	52	298	Environmental -side (776)
Regulatory controls	145	46	34	225	
Advocacy guidance	86	14	63	163	
Tax benefits	0	85	5	90	
Market control	82	82	14	178	Demand-side (472)
Government purchases	168	0	0	168	
Strategy measures	35	0	0	35	
Cooperation and outsourcing	49	42	0	91	
Total	1,199	814	219	2,232	
percentage	53.72%	36.47%	0.0981	100%	

TABLE 10 Distribution of "Dual Carbon" policy objects in achieving policy goals.

Objects instruments	Ecological green transition	Economic green transition	Social green transition	Total	Percentage (%)
The government	934	115	116	1,165	52.81
Businesses and organizations	336	429	49	814	36.90
The public	56	29	142	227	10.29
Total	1,326	573	307	2,206	100

dioxide production and emission. One way to promote and direct their engagement in energy-saving and emission-reduction initiatives is to strengthen tax profits. On the other side, China need control, monitor, and assess their behavior in order to foster a positive work environment. For the general public, it is essential to directing citizens' behavior in daily life through publicity, education, and appropriate acknowledgment, reward, and punishment.

4.2.3 Analysis of Y-Z dimension results

Cross-tabulation analysis of the Y-Z dimensions was carried out (Table 10), The total coding for policy goals and objects was 2,303 and 2,232, respectively, while they were cross-coded with 2,206, indicating the presence of one-to-many and many-to-one relationships.

Inferred from the cross-tabulation data, the policy objects with the highest frequency of response for the government, businesses and organizations, and the general people are, respectively, ecological green transformation, economic green transformation, and social green transformation. The tasks of the government, businesses, and organizations, and the general public in the "Dual Carbon" tracks are aligned with this situation: the government is primarily responsible for resource, environmental, and ecological issues, and focusing on the implementation of ecological green transformation is its top priority; Businesses and organizations are more concerned with enhancing economic efficiency and lowering the costs associated with energy conservation and emission reduction due to their role in pursuing economic benefits and development; consequently, policies for businesses and organizations place a focus on achieving the goals of economic green transformation, such as industrial upgrading, innovation in the green financial system, and optimization of the energy structure; Since the public is the driving force behind the social green transition, encouraging and enabling them to actively participate in ecological and environmental sustainability is essential to accomplishing the "Dual Carbon" target.

4.3 Results of the three-dimensional cross-tabulation analysis

Cross-tabulation analysis of the X-Y-Z dimensions (Table 11), discovered that there were significant disparities in the kinds of policy instruments that acted on various policy objects and were put into place in response to various policy goals. Among the policies to achieve the goal of ecological green transformation, supply-side

TABLE 11 Use of "Dual Carbon" policy instruments by policy objects to achieve policy goals.

Instruments		Ecological green transition			Economic green transition			Social green transition			Total
		The government	Businesses and organizations	The public	The government	Businesses and organizations	The public	The government	Businesses and organizations	The public	
Supply-side	Talent training	15	12	0	4	16	0	3	2	1	980
	Financial support	261	167	2	47	138	13	18	5	6	
	Infrastructure	34	18	8	6	25	7	16	6	6	
	Information services	53	21	4	2	49	0	3	8	4	
	Subtotal	363	218	14	59	228	20	40	21	17	
	percentage	39.29%	61.24%	27.45%	51.30%	56.58%	68.97%	38.46%	42.86%	12.23%	
Environmental-side	Target planning	118	35	5	14	35	1	23	2	46	745
	Regulatory controls	116	6	7	8	33	1	9	7	26	
	Advocacy guidance	67	5	19	13	5	4	6	4	40	
	Tax benefits	0	37	0	0	39	0	0	9	5	
	Subtotal	301	83	31	35	112	6	38	22	117	
	percentage	32.58%	23.31%	60.78%	30.43%	27.79%	20.69%	36.54%	44.9%	84.17%	
Demand-side	Market control	82	32	6	0	46	3	0	4	5	445
	Government purchases	138	0	0	9	0	0	16	0	0	
	Strategy measures	24	0	0	8	0	0	3	0	0	
	Cooperation and outsourcing	16	23	0	4	17	0	7	2	0	
	Subtotal	260	55	6	21	63	3	26	6	5	
	percentage	28.14%	15.45%	11.76%	18.26%	15.63%	10.34%	25%	12.24%	3.6%	
Total		924	356	51	115	403	29	104	49	139	2,170
total percentage		42.58%	16.41%	2.35%	5.3%	18.57%	1.34%	4.79%	2.26%	6.41%	

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acting on the government, businesses, and organizations are more frequently used, whereas the public uses environmental-side more frequently; among the policies to achieve the goal of economic green transformation, the policies acting on the three sides of objects are concentrated on the supply-side; among the policies to achieve the goal of social green transformation, the supply-side affecting the government are more frequent, whereas the environmental-side affecting businesses, organizations, and the general public are more prevalent. It is evident that the supply-side have a stronger influence and penetration power on governments, businesses, and organizations; the environmental-side have a stronger influence and penetration power on the public to achieve social green transformation, and the pulling power of the demand-side needs to be strengthened.

5 Discussion

5.1 The analysis of results

5.1.1 Differences in the popularization and implementation of provincial "Dual Carbon" policies

Currently, China's local "Dual Carbon"" policy system is in its infancy. As of 31 December 2023, 31 provincial-level administrative regions, excluding Hong Kong, Macao, and Taiwan, have issued relevant policies. Among them, Shanghai (13), Jiangxi (12), Jiangsu (10), and Hunan (8) have issued a relatively large number of policies, indicating that these provinces have a high awareness of the need to take action to address climate change and to achieve the goals of carbon peaking and carbon neutrality, as well as strong policy implementation. These regions tend to have heavier responsibilities for carbon emissions, and the effect of policy implementation is of great significance to the realization of the "Dual Carbon" target of the country as a whole. Hubei and Tibet, on the other hand, have only issued one special policy on carbon emissions, reflecting the relatively low level of resource investment and policy attention in the formulation and implementation of carbon policies in these regions. These regions may need to strengthen their efforts in policy development and implementation in order to maintain overall synchronized progress with the achievement of the national "Dual Carbon""target.

5.1.2 Uneven distribution of policy instruments and internal and external disproportionality

It is found that the supply-side policy instruments account for a relatively high proportion (43.52%), followed by the environment-side (35.82%), and the demand-side policy instruments (20.67%) are relatively low. Demand-side policy instruments are seriously insufficient, and the gap between the use of the other two sides of policy instruments is large; internally, there is a polarized phenomenon of overflow and serious underuse of policy instruments, with only the three sides of policy instruments of financial support, target planning and publicity and guidance accounting for 50% of all policy instruments, but the four sides of talent cultivation, tax incentives, policy synergies and exchange platforms account for a total of only 11.9%. Among environment-oriented policy instruments, tax incentives account for only 4.16% of all policy instruments, indicating that insufficient attention is paid to tax incentives.

5.1.3 Incomplete coverage of policy goals and shortcomings in layout

Statistically, the ratio of policy provisions covering the three sides of policy goals is 4.6:1.9:1, which indicates that the current focus on the goal of a green transformation of society is insufficient. To advance multiple goals simultaneously, policymakers should consider increasing the attention paid to the goal of a green societal transition to ensure that policy goals are holistic and comprehensive.

5.1.4 The combined role of policy objects is underutilized

Through statistics, it is found that the policies that act on the government are overused, accounting for a total of 52.72%, enterprises and organizations for 36.47%, and the public for 9.81%. This indicates that the current policy text lacks mechanisms and institutions for enterprises organizations and the public to participate in "Dual Carbon"" actions, resulting in a distribution pattern in which multiple parties are not able to participate, and causing resistance to the "Dual Carbon"" implementation path of synergistic participation by multiple actors.

5.1.5 Low degree of matching between policy dimensions

The key to achieving a balanced match between policy instruments, policy goals, and policy objects is improving the high degree of coupling of policy instruments with multiple objects and goals and expanding the comprehensiveness of the coverage of the three main sides of instruments with policy objects and policy goals. To bring into play the cross-cutting effects and strengthen the scientific nature of the "Dual Carbon" policy, the synergistic use of supply-side, demand-side, and environment-side should be encouraged. Policies should also be applied precisely and effectively to the government, society, organizations, and the public following the pattern of ecological, economic, and social development.

5.2 Policy recommendations for the government

5.2.1 Strengthening the popularization and implementation of "Dual Carbon"" policies nationwide

In response to the results of the analysis, it is necessary to strengthen the popularization of the "Dual Carbon"" policy nationwide, improve the implementation of the policy, and encourage local governments to formulate and adjust policy measures according to the actual situation. At the same time, it is necessary to promote cross-regional policy experience sharing and cooperation, facilitate policy transparency and communication, and establish an effective multi-party collaboration mechanism. In addition, monitoring and evaluation of policy implementation should be strengthened, and a comprehensive performance evaluation system for policy implementation should be

established to ensure that the effectiveness of regional "Dual Carbon"" policies is clearly and comprehensively assessed. The combined application of these recommendations will help to improve the promotion and implementation of regional "Dual Carbon"" policies in China and facilitate the formation of a favorable atmosphere for national policy implementation.

5.2.2 Adjusting the structure of policy instruments to realize the combined effect

Through analysis, it is found that the current sides of "Dual Carbon"" policy instruments are characterized by strong supply, light environment, and weak demand. Although the supply-side policy instruments account for a large proportion of the policy instruments and provide strong support for the realization of the "Dual Carbon"" goal, the insufficiency of demand-side policy instruments also restricts the policy effect. To balance the configuration of policy instruments, it is necessary to adjust the external and internal structure of policy instruments, to form a combination effect of "Dual Carbon"" policies and play a clustering role. In addition, we note that green tax incentives are relatively underutilized among environmental policy instruments. To unleash their incentive potential, policymakers should pay more attention to and implement green tax incentives and other preferential policies to create a market environment conducive to carbon emission reduction.

5.2.3 Optimizing the layout of policy goals and enhancing the comprehensiveness of policies

In terms of policy goals, the ecological green transformation goal is more prominent, while the attention to the social green transformation goal needs to be improved. In the future, attention to policies for realizing social green transformation goals should be increased, focusing policies on establishing a green public service system and carrying out green education for all, establishing and improving the support system for urban and rural residents to live green, strengthening citizens' low-carbon beliefs, and cultivating public low-carbon consumption behavior. In addition, policies for regulating and punishing behaviors that harm the ecological environment need to be increased, and a strategy combining incentives and guidance with punishment needs to be adopted, to Form a healthy and orderly policy environment.

5.2.4 Strengthen the synergy of policy objects and consolidate the support system of policies

Regarding policy objects, the results show that the government, enterprises, and organizations account for a relatively large proportion, but the public accounts for a relatively small proportion. We propose to build and improve a multi-participation mechanism to encourage and guide enterprises, organizations, and the public to participate in achieving the "Dual Carbon"" goal. First, at the level of enterprises and organizations, policies should be focused on stimulating the participation of enterprises and organizations in energy saving and emission reduction activities, strengthening the financial and tax support for enterprises to participate in energy saving and emission reduction activities; increasing the intensity of government projects and government purchasing; improving the carbon trading market mechanism and green financial system; introducing the Interim Regulations on the Administration of Carbon Emission Trading to regulate the behavior of enterprises and the market order; and encouraging colleges, universities, and scientific research institutions to carry out research and development of green and low-carbon technologies and accelerating the transformation of scientific and technological achievements. Technology research and development and accelerate the transformation of scientific and technological achievements. Secondly, at the public level, we should explore innovative policies for public participation in energy conservation and emission reduction activities, build a national action system to promote the greening of lifestyles, and formulate corresponding commendations, rewards, and penalties, to guide citizens' behavior and turn low-carbon concepts into conscious actions by the public.

5.2.5 Improving the coupling and coverage of policy matching to leverage cross-cutting effects

According to the two-dimensional and three-dimensional cross-tabulation analysis, we find that there are obvious differences between policy instruments across policy goals and objects. It is recommended to improve the high degree of coupling of policy instruments with multiple objects and goals and to expand the comprehensiveness of the coverage of the three major sides of instruments with policy objects and policy goals. The synergistic use of supply-side, demand-side, and environmental-side policy instruments should be promoted, and policies should be applied accurately and efficiently to the government, society, organizations, and the public following the pattern of ecological, economic and social development, to give full play to the cross-cutting effects and enhance the scientific nature of the "Dual Carbon" policy.

6 Conclusion

Based on the three-dimensional analysis framework of policy instruments, goals and objects, this paper selects 203 "Dual Carbon" policy texts, carries out a multi-dimensional quantitative analysis of "Dual Carbon" policy, and puts forward targeted relief strategies, which is not only of innovative significance in expanding the orientation of theoretical research, but also of practical value in optimizing the purpose of practical governance. The number of strategies is rather small because the "Dual Carbon"target plan has only been available for 2 years. We will continue to expand the samples of policy analyses and integrate them with the logic of policy evolution to better understand how China's "Dual Carbon" policy framework is evolving and how policy effects are manifesting going forward. We will keep expanding the sample of policy analyses and conduct ongoing, multi-dimensional research and explorations by fusing the logic of policy evolution, policy system, and policy effectiveness in the future with the continuous improvement of China's "Dual Carbon" policy system and the further manifestation of policy effects.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2024.1418253/full#supplementary-material

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A review of Global Carbon Markets from Kyoto to Paris and beyond: the persistent failure of implementation

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This review article provides a comprehensive multidisciplinary and in-depth analysis of how the idea of Global Carbon Markets (GCM) has evolved from the Kyoto Protocol to the Paris Agreement and the post-Paris Agreement period (2015–2022) and why no real consensus has been reached after 25 years of negotiations, based on the categorisation of different arguments from different authors. We apply a semi-systematic review to 32 scientific articles, special reports, and relevant websites to analyse the failure in reaching international consensus on GCM. We apply three dichotomies, market vs. non-market-based approaches, top-down vs. bottom-up and national vs. international level. There are two striking findings. First (out of the articles that can easily be placed along all three dichotomies), there is an overwhelming majority of articles combining market-based, top-down, and international level explanations. This is however countered by a second finding, namely, that there is also a clear historical trend which is unlikely to change away from top-down and towards bottom-up approaches since the Paris agreement, combined with a movement towards more non-market-based and national approaches.

KEYWORDS

global carbon market, Paris agreement, Kyoto protocol, article 6, negotiation

1 Introduction

Since the Kyoto protocol (KP) in 1997, carbon markets have emerged as a main politico-economic tool in global efforts to address climate change (Böhm et al., 2012). The idea of Global Carbon Markets (GCM) was first introduced under the KP as one of the so-called flexibility mechanisms, i.e., the joint implementation schemes and clean development mechanism. These are mechanisms that constitute attractive options due to their potential to exploit cost-effective mitigation potential and activate the private sector

Abbreviations: Ar6, Article 6; CDM, Clean Development Mechanism; CER, Certified Emission Reductions; COP, Conference Of Parties EU ETS European Union Emissions Trading System FVAs, Framework for Various Approaches; GCM, Global Carbon Markets GHG Greenhouse gases; IET, International Emission Trading; IPCC Intergovernmental Panel on Climate Change; JI, Joint Implementation; KP Kyoto Protocol NDC, Nationally Determined Contributions; NMA, Non-Market-based Approach; PA, Paris Agreement; REDD+., Reducing Emissions from Deforestation and forest Degradation Definition; SBSTA Subsidiary Body for Scientific and Technological Advice; UNFCCC, United Nations Framework Convention on Climate Change.

(Höhne et al., 2015). The Paris Agreement (PA) provides for global markets by acknowledging that states, if working together to implement their Nationally Determined Contributions (NDCs), may exchange mitigation outcomes under their own authority, and utilize new mitigation mechanisms. However, implementation has yet to be determined, both nationally and internationally, and the Parties disagree on major points. This creates challenges, not only in terms of creating markets that allow and accommodate international remittances, but also in terms of the long-term connecting of markets across multiple domestic jurisdictions (Stavins and Stowe, 2017). Although GCM discussions have been part of the COP climate meetings for more than 20 years, there is little to suggest that GCM will be implemented in the foreseeable future. There have been national and regional attempts to create carbon markets, but no success at the global level in implementing a functioning market.

By carbon markets we understand markets in which carbon credits are obtained and sold within defined standards to cost-effectively reduce the emission of carbon dioxide (CO_2) and other greenhouse gases (Ozcan and Ozturk, 2019). GCM are made up of voluntarily interconnected markets producing and trading broadly similar products, where the markets are interconnected enough for major price differences between regions to be arbitraged (Pollitt, 2019). We argue that GCM is the evolution of the KP's international carbon market during the post-Kyoto phase, following the inclusion of cooperative mechanisms in the PA to promote greater international co-operation and improve the cost-effectiveness of GHG emission reductions through the disposition of Article 6 (Ar6) of the PA and its various market and non-market mechanisms. GCM is thus a further development of international cooperation on the carbon market cooperation, as the GCM links different systems and can thus facilitate the transition from the flexibility of the KP to the cost efficiency of the PA and cross-border rules. Therefore, the GCM continues and supports international co-operation on emission reductions under the PA, reduces price volatility and lowers costs by improving access to cost-effective emission reduction options. We see GCM as a mechanism that fits into the toolkit of UNFCCC negotiations that promote and advance international cooperation to facilitate emissions reductions.

There are many reasons why GCM is a worthy focus for a review article. GCM is an important potential component of NDCs, which is the key process Ar6 of the PA, allowing countries to be more ambitious by being more flexible; the global market could be used for international climate finance, independent of national contributions; and the mechanisms of the GCM, domestic and other carbon pricing policies are used to implement the international offers domestically and enhance global climate action.

We proceed as follows. Section 2 presents the methodology, Sections 3–6 constitute a historical description of how the debate on GCM, including key concepts and developments, has evolved, organized around the COPs, and ending with the 2021 COP 26. Section 7 discusses the main arguments and reasons for GCM implementation failure. Here, as a simple heuristic by which to organize the literature, we suggest three very basic dichotomies derived from the political economy literature, market vs. non-market approaches, top-down vs. bottom-up processes, and national and international level approaches. Section 8 provides a summary of the discussion and 9 a brief conclusion. The approaches towards GCM have varied over time and there is still no consensus on how to implement it. There are however two striking findings. First, the overwhelming majority of articles attempting to explain the failure to implement GCM combine market-based, top-down, and international level explanations. This is, however, countered by a second finding, namely, that there is also a historical trend–which is unlikely to change–essentially since the PA, away from top-down and towards bottom-up approaches. This is combined with a possible movement towards more non-market-based and national approaches. Thus, in trying to explain the failure of the implementation of a GCM, since the PA there has been a shift in the literature. Since the PA, much of the literature has focused on Ar6, which has created an environment that enables international cooperation on carbon markets. The observed shift from top-down to bottom-up is essentially a shift from the flexible mechanisms of the KP to the cost-effectiveness instruments under Ar6 of the PA.

2 Methodology

Hart (1998) defines the literature review as "the use of ideas in the literature to justify the particular approach to the topic, the selection of methods, and demonstration that this research contributes something new". Among the types of reviews, we find systematic, semi-systematic, and integrative reviews. This is a semi-systematic review. The semi-systematic, sometimes narrative, review approach is structured for issues that have been conceptualized in a variety of ways and in different disciplines. Semi-systematic reviews often look at how research within a selected field has progressed over time or how a topic has developed across research traditions. Specifically, the analysis aims to recognize and explain applicable research patterns that have consequences for the topic under study and to synthesize those using meta-narratives (Wong et al., 2013). A thematic or content analysis is commonly used and can be broadly defined as a method for identifying, analysing, and reporting patterns in the form of themes within a text (Braun and Clarke, 2006).

Our main objective is to investigate the function of carbon markets in climate change negotiations with a focus on why the implementation of GCM has been mainly unsuccessful. We have used databases such as Google Scholar, Web of Science, and Scopus to search for qualitative social science publications and research papers in peer-reviewed English language journals for specialised research on carbon markets and climate change (e.g., Climate policy journal, Journal of Economic Perspectives, WIREs Climate Change, Carbon Management). To narrow down the list of possible literature and the search for journals and articles, we have used the search term "GCM" for the period 2008-2021. We used 2008 as our starting year, inspired by critical points made by Michael Wara in his *Nature* article "Is the global carbon market working?", where he discussed the success and failure of the Clean Development Mechanism (CDM) (Wara, 2007).

Our original search, based on the Google Scholar engine yielded roughly 18,000 results. Both empirical and theoretical articles were considered. In a second step, we developed a simple search strategy based on the Google Scholar engine, with inclusion and exclusion criteria on three levels, with the aim of identifying the number of relevant articles and narrowing them down (see Table 1, below (2A, 2B, 2C)).

TABLE 1 Article selection.

Steps	Descriptions	Results
Step1-Identification- Google scholar engine	Total number of literatures identified by the database search including citations	N = 18000
Step2A-Identification- Google scholar engine	Sorting by relevance, review articles	N = 2,300
Step2B-Identification- Google scholar engine	Sorting by date, relevance, review articles	N = 1,600
Step2C-Identification- Google scholar engine	Sorting by date, any type	N = 150
Step3-Screening- Google Scholar advanced search engine	Review of literature	N = 52
Step4-Screening- Google Scholar advanced search engine	Focus on title and abstract	N = 34
Step5-Eligibility-	Assessment of full text literature	N = 33
Step6-Included-	literature included in the analysis	N = 32

In step 2A, we selected the following options one by one: We selected sort "by relevance" in the Google Scholar field search to find and match search keywords- + review articles; these studies have a literature review or refer to the literature review- + global "carbon markets". This brought us down to about 2,300 articles. For step 2B, we applied this strategy and selected the following options one by one: 2008-2021 + sort by relevance- we selected the "by relevance" option in the Google Scholar field search to find and match search keywords- + review articles-these studies have a literature review or refer to the literature review- + global "carbon markets". This yielded roughly 1,600 articles. In step 2C, we selected the following options one by one: 2008-2021 + sort by date + any type. We selected "any type" in Google Scholar to filter the search results by any type of literature + global "carbon markets". This brought us down to approximately 150 articles.

In step 3, we narrowed the selection to articles with a literature review in one form or another, as sorted through the individual boxes of Google Scholar's advanced search engine with all words (review carbon markets), with the exact phrase (carbon markets), with at least one of the words (review), where my words occur–we selected "Where my words occur" in Google Scholar to find the words in the body of the article, not just in the title of the article (=anywhere in the literature).

In the final steps, we focused on exact titles and abstracts as follows: with all the words (global carbon markets), with the exact phrase (carbon markets), with at least one of the words (review), where my words occur–we selected "where my words occur" in Google Scholar to find the words in the body of the article, not just in the title of the article—(anywhere in the article) and it showed us global carbon markets review "carbon markets". We then read the 33 selected pieces and excluded books and works published in non-English-speaking countries. Finally, we focused exclusively on qualitative studies published in peer-reviewed English language journals (i.e., the topic of the study followed this string: Global carbon markets + Kyoto Protocol + Kyoto mechanisms + Paris Agreement + Article6). This took us down to 32.

We conducted an in-depth analysis by reading and coding the 32 articles to identify and extract constitutive concepts based on GCM background (Sections 3–6), argumentation patterns (Section 7.1), approaches and/or dichotomies (Section 7.2). We also manually coded the literature to develop three dichotomies based on a semi-systematic review. Section 7.2 and its subsections describe our process of literature review from unstructured information to a structured and theoretically grounded three-level lens.

3 Background: the starting point of the global carbon market

The starting point for carbon markets was article 4.2 of the UNFCCC[1] with its joint implementation Greenhouse Gas Emissions (GHG) mitigation rule, initiated by mainly Western countries seeking to create a window for the development of market mechanisms. Newell et al. (2013) claims the KP as the birthplace of GCM: European and other developed countries wanted to take action to reduce GHGs under the KP, and a global carbon trading market was a key approach. In the 1995 COP1 climate conference in Berlin, a pilot phase of "Activities Implemented Jointly" (AIJ) was launched (Korppoo, 2005). At the COP2 in Geneva, representatives and delegates constructed policies to speed up the negotiation process. The US announced that it would accept legally binding agreements if other states did, calling for all states to contribute (Rosenzweig, 2016). The KP was adopted at the 1997 COP3 in Kyoto and Article 3 set a market demand for GHGs by imposing binding reductions (Michaelowa and Schmidt, 1997). In the KP, the 38 countries listed in the so-called Annex I shall, on the basis of Article 3 (1) and (1 bis) of the KP, individually or jointly, ensure that their aggregate anthropogenic carbon dioxide equivalent emissions of the GHGs listed in Annex A do not exceed their assigned amounts, calculated according to their quantified emission limitation and reduction commitments inscribed in Annex B and following the provisions of this Article, to reduce their overall emissions of gases by at least 5 percent below 1990 levels in the commitment period 2008-2012. The KP established GHG reduction targets for 38 developed states and economies in transition–Annex B Parties to the Protocol. These mitigation targets were enounced in countries' emissions allowances (Shishlov et al., 2016). Countries that have committed to limiting or reducing their GHGs under the

1 See Article four commitments under FCCC/INFORMAL/84 GE.05-62220 (E) 200705 here: https://unfccc.int/resource/docs/convkp/conveng.pdf.

KP must achieve their targets primarily through national action. As an additional means to achieve these goals, the KP introduced three supplementary mechanisms, namely, the emission targets of Annex B countries, to initiate the creation of GCM. Annex B Parties could use the GCM and its three market mechanisms for emissions trading, as set out in Article 17 of the KP, to optimise economic efficiency in meeting their carbon reduction or limitation targets (Morgan, 2006). We can link various Kyoto mechanisms and markets to the GCM. These flexible mechanisms, such as the CDM under the GCM, are an effective synergy between developed and developing countries, providing an opportunity to reduce emissions and learn about and benefit from the GCM and Kyoto mechanisms. Thus, annex B Parties might use three market mechanisms to optimize the economic efficiency of meeting their carbon reduction or restriction goals.

3.1 International emission trading (IET)

IET is a bilateral cap-and-trade system trading pre-assigned allowances among mitigating states (Annex I Parties) to enable flexibility to help countries reach their Kyoto commitments. Kyoto also allowed issuance and trade under the IET of removal units (Carbon Markets under the Kyoto Protocol, 2018).

3.2 The clean development mechanism (CDM)

CDM is a program-based, baseline-and-credit system at the enterprise level. It allows projects in non-mitigating states to produce carbon savings (Certified Emission Reductions, or CER) that can be purchased by governments and private sector institutions and thus asserted by mitigating countries for compliance reasons (Cole, 2010).

3.3 Joint implementation (JI)

JI helps projects to produce carbon assets identified as Emission Reducing Units (ERUs) among mitigating countries. For KP compliance purposes ERUs created in one country may be claimed by another. JI has two channels: channel one enables states to produce ERUs without international supervision; and channel 2, in which the JI Supervisory Committee oversees the initiatives and the generated emission-reducing units (Shishlov et al., 2012).

These mechanisms are the basis for the regulated global compliance carbon market. Based on the 2007 analysis of the World Bank, the JI market of the KP traded only 41 million tonnes (Mt) of carbon. To meet the protocol obligations states have established emission trading systems. The largest of these is the EU Emission Trading Scheme (EU ETS) which allows trading between EU member states *via* the above mechanisms. By the end of its first year of trading, the EU ETS had transacted an estimated 362 Mt of carbon credits, worth approximately €7.2 billion (US$9 billion). The explosive growth of the global compliance carbon market under the KP has meant that prices for carbon credits have been extremely volatile. Between 2009 and 2018, the price rarely exceeded €20 per metric tonne of carbon and dropped to only €3 in 2013. However, in the post-Covid economic recovery, from 2021 to early 2023 the price of emission allowances rose to €70-100. From March 2023 onwards, they fell by more than €15 per tonne due to the acceleration of the European Green Deal and the inclusion of nuclear power and natural gas as green energy sources (Trading Economics, 2024; Wojciechowski et al., 2023).

4 Toward an effective new GCM: Ar6 and the establishment of the carbon market system under the PA

Copenhagen (COP15, 2009) did little to advance the development of a GCM. A disappointing meeting in combination with an underperforming EU ETS and a worldwide economic crisis, left the GCM idea in a critical state. Also, the largest emitters seemed to have no strong interest in emissions reductions. However, with Cancun (COP16, 2010) and Durban (COP17, 2011) came new promise. In Cancun it was agreed to consider setting up market mechanisms to increase the cost-effectiveness of mitigation measures and develop market mechanism rules (Gao et al., 2019). The creation of a new market mechanism was a red line for many Parties–no new market mechanism, no Durban deal. COP17 formally recognized two international carbon markets. CDM and JI would proceed as attempts to gain increased efficiency by providing more efficient and consistent regulation (Marcu, 2012b).[2] Post-Durban, there was however little progress,[3] until COP21 in Paris reintegrated international carbon markets (Koakutsu et al., 2016).

Article 6 (Ar6) of the PA provides for voluntary cooperation between Parties to implement their NDCs. Therefore, Ar6 mechanisms are supplementary—"a basis for creating new linkages between different jurisdictions to reduce the current fragmentation of carbon markets" (World Bank Group, 2019: 11).

To Leggett (2020), Ar6 allows for the use of market mechanisms as an additional mechanism to achieve GHG reductions at the lowest possible cost and in line with sustainable development (Article 6.1). To substantiate and support this approach, a study by the Public Policy Research Institute of the US Congress argues that Ar6 allows the use of market mechanisms to achieve GHG reductions at the lowest possible cost and consistent with sustainable development. Some scholars (e.g., Blum, 2019) believe that Ar6 provides incentives for the creation of a GCM. Moreover, carbon markets enable

2 Several decisions were made regarding carbon markets CDM/JI. Draft decision-/COP17/CMP7 Modalities and procedures for carbon dioxide capture and storage in geological formations as clean development mechanism project activities under UNFCCC (https://unfccc.int/files/meetings/durban_nov_2011/decisions/application/pdf/cmp7_carbon_storage_.pdf) and Draft decision -/COP17/CMP7 Guidance on the implementation of Ar6 of the Kyoto Protocol (https://unfccc.int/files/meetings/durban_nov_2011/decisions/application/pdf/cmp7_guidance_article6.pdf).

3 See Koakutsu et al. (2016), e.g., Decision 1/CP.19 Further development of the Durban Platform (https://unfccc.int/resource/docs/2013/cop19/eng/10a01.pdf).

countries to meet the climate targets of their NDCs (Schneider and Stephanie, 2019). Ar6 developed two international carbon markets under Articles 6.2e6.3 Cooperative Approaches and the Sustainable Development Mechanism under Articles 6.4e6.7 (UNFCCC, 2015). Articles 6.2 and 6.3 form the basis for the right to manage and use internationally transferred mitigation outcomes among Parties as a particular case of "cooperative strategies" in their NDCs. 6.2 states that Parties participating in internationally transferred mitigation outcomes "shall promote a sustainable environment and ensure environmental integrity". In this context, paragraphs 6.2 and 6.3 are "transfer paragraphs", which provide the means for a process that may lead to convergence of domestic carbon prices over time (Marcu, 2016). Articles 6.4 and 6.7 are mechanisms that contribute to the reduction of GHGs and support sustainable development (Marcu, 2016).

5 GCM beyond the PA: the contribution of COP24

The threshold for the PA to come into effect–formal adoption by 55 states representing at least 55 percent of global emissions–was reached by 4 October 2016. By the end of the 2016 COP22 in Marrakech, it had been ratified by 111 states accounting for more than 75% of global emissions (UNFCCC, 2021). Marrakech was a turning point. On GCM, countries took ambitious action in which the Parties formulated long-term, low-carbon development strategies (PA, Article 4.19). They also sought to facilitate the widespread exchange of resources, knowledge, and experiences with deep decarbonisation planning. The result was a commitment by 22 countries, 15 cities, 17 states, and 196 businesses. In addition, the US, Mexico, Germany, and Canada had already published their own strategic documents (Danyluk, 2017). At COP23 - the climate meeting in Bonn in 2017 - governments took the next step towards an operating system to realise the potential of the PA, including the PA Adaptation Fund. The Fund represents the Parties' call for the PA to help decarbonize nations, as well as adjust and develop resistance to climate change (Peet et al., 2017). A delegate representing the Alliance of Small Island States (AOSIS), for instance, argued, that the Adaptation Fund is a critical component of the financial architecture for decarbonizing of the economy. Developing states highlighted specific features of the Fund to underpin their support.

Within three years of the PA, the Intergovernmental Panel on Climate Change (IPCC) had released a special report on 1.5 degrees of global warming, as requested at Paris (Erbach, 2019). In 2018, COP24 took place in Katowice, Poland, where an international rulebook for the efficient implementation of the PA was implemented. However, Ar6 was the one item on the agenda not to join the rulebook (COP24, 2018).

Within the Transparency Framework (PA, Art. 13), the Parties could only agree on minimum requirements to safeguard the environmental integrity of Ar6 (Obergassel et al., 2018:9). The Parties worked through multiple issues and established common ground on many. Advancement on carbon markets was seized in two sets of reports: The draft texts on Article 6.2, 6.4 and 6.8 negotiated upon by the Subsidiary Body for Scientific and Technological Advice (SBSTA 49), and the written recommendations on the three agenda items of the Katowice presidency. The Parties decided on a variety of draft issues, but continued to face stumbling blocks, leaving Ar6 without formal agreement on GCM or international collaboration. Centralized process and double-counting problems remain extremely controversial in the accounting of international transfer under Article 6.4. Problems, such as the transfer of CDM programs, credits, and methodologies to Article 6.4, the share of adaptation proceeds imposed under Article 6.4, and the liability of Reducing Emission from Deforestation and forest Degradation (REDD+), also remain available. Thus, the full implementation of Ar6 was postponed until the 2019 COP25. Thus, carbon markets remained in limbo (Greiner et al., 2019).

6 The COP25 summit: GCM in limbo

The 2019 COP25 occurred under the administration of the Chilean government but was eventually hosted in Madrid. A central goal was to complete issues on the full operationalization of the PA rulebook. The climate change conference included the 51st meetings of the subsidiary implementation body and the SBSTA to help strengthen both commitments and address issues related to the sustainable development framework, market mechanisms and non-market Ar6 mechanisms in the context of the PA (Asadnabizadeh, 2019).

COP25 also aimed at developing a process for GCM (under Ar6 of the PA). It had an important role in bringing the PA into force and paving the way for more ambitious carbon reduction commitments at COP26. COP25 aimed to develop guidelines on the development of international carbon markets (KPMG, 2019), with global cooperation on GCM cooperation the top priority. After leaving COP24 without results on Ar6, negotiators continued to work towards an agreement before countries focused on preparing their next crucial round of NDCs (Hanafi, 2019). At the forefront was GCM and carbon trading rules, as set out in Ar6. Talks however failed to generate results (Kouchakji, 2020).

Ar6 loomed large over the event, and the guidelines for global market mechanisms in the PA also earned conspicuous attention from environmental NGOs, underscoring the prominence of the issue (IETA, 2019). Patricia Espinosa, Executive Secretary of UNFCCC, emphasized that "We need to be clear that the conference did not result in agreement on the guidelines for a much-needed carbon market–an essential part of the toolkit to raise ambition that can harness the potential of the private sector and generate finance for adaptation". The main obstacles against agreement on GCM were: first, rules to prevent double counting, where both the states buying emissions reductions and the states selling them could end up counting these reductions in their own NDC targets; second, smoother transition of carbon credits from the Kyoto mechanism into the PA; and third, the 'share of proceeds' that would be set aside for climate change adaptation in vulnerable countries. Additionally, Australia and Brazil demanded a carryover of Kyoto credits, while Brazil also wanted to use double counting (Chandramouli, 2019; Streck, 2020).

The GCM marathon continued in 2021. After a 1-year Covid hiatus, COP26 was hosted in Glasgow, Scotland. It yielded the

Glasgow Climate Pact, a plethora of high-level sectoral pledges, and a set of decisions that complete the Paris Rulebook by operationalizing Ar6. Parties approved decisions on three elements of Ar6: article 6.2 (cooperative approaches involving the use of internationally transferred mitigation outcomes for NDCs); 6.4 (a mechanism that contributes to mitigation and supports sustainable development); and 6.8 (non-market approaches) (IETA, 2021:3). In 2028, consideration will be given to whether additional safeguards or restrictions on the use of credits under 6.2 should be applied. A supervisory authority under article 6.4 will start work in 2022 and develop methodologies and administrative requirements. A Glasgow committee on non-market approaches has been established for the development of climate cooperation under article 6.8.[4] Thus, at COP26, the GCM idea made some definite forward steps, but the big breakthroughs necessary for the new NDC pledges to become reality still elude us. Ahonen et al. (2022) similarly argue that the negotiations on carbon markets from Kyoto to Paris that was not successful at COP24 in Katowice in 2018, persisted at COP25 in Madrid in 2019 and could only be partially resolved at COP26 in 2021. True, Glasgow addressed double counting of carbon credits bought and sold through the multilateral mechanism advocated in paragraph 6.4 of the Agreement. However, double counting arising from voluntary commitments by the private sector commitments remain outside the system (Hunter et al., 2021).

7 Discussion

In the following, we first provide a selective overview of some of the most important GCM arguments with respect to the failure of GCM implementation. Thereafter, we suggest three dichotomies all derived from the political economy literature that these arguments can be organized according to: market vs. non-market mechanisms, top-down vs. bottom-up processes, and national vs. international level. We obviously do not suggest that this is the only way to organize the literature. Our purpose is to provide a simple heuristic by which to narrow down the field to more easily be able to say something about where the literature puts the blame for the failure of GCM implementation. We do not present any overarching theoretical framework, but we believe that our heuristic holds immediate relevance for GCM, as well as captures some historical trends in the development of GCM. Non-market approaches have been an issue of contention with respect to GCM for a couple of decades already. The tension between bottom-up and top-down solutions has been obvious since the inception of the COP system, and a tension where we see a clear tendency since the PA that solutions are ever more sought bottom-up than through overarching, mutually binding frameworks from major international conferences. Finally, there is some overlap between the previous dichotomy and the national vs. the international level. However, in the latter we focus on the actual behaviour of major national actors and the leadership (or lack thereof) exhibited by such actors in influencing the development of GCM. This is another dichotomy that is highly relevant for GCM, as there is little doubt that the active agency of major actors is often a requirement for policy change. It goes without saying that not all the 32 articles reviewed were easily categorized along these dichotomies. We do however think that this organization gives us a decent overall view of the literature.

7.1 A select overview of substantive GCM arguments

Here, we seek to provide a summary of the arguments about GCM in the context of the issues discussed in Sections 3–6. We then outline core arguments from the COP debates, showcasing the many different views on GCM and GCM implementation failure. Our aim is to demonstrate that GCM are not simply automatically formed. On the contrary, a plethora of theoretical and empirical arguments have been considered in UNFCCC negotiations.

1997 through 2001 saw several COP meetings but negotiations were economically inefficient and politically impractical. Neither of the standard market-based environmental policy instruments were viable: a tradable permit system would be inefficient, and an emissions tax politically unrealistic (McKibbin and Wilcoxen, 2002). Schiermeier (2012) argues that the seeds of Kyoto's problems (COP3) were planted long before the treaty. The 1995 COP1 in Berlin divided the world into two. There would be a set of rich states with ambitious climate responsibilities and a set of less-developed states without responsibilities. This did not sit well with US politicians. Many policy experts believe that the UNFCCC and the KP failed to win over the biggest polluters because it was linked to ethical and environmental rationales. To Roger Pielke (cited in Schiermeier, 2012, p. 658) "making energy more expensive is a political liability everywhere. When emission reductions run up against economic growth, economic growth will inevitably win out. There is no magical solution, so you better set yourself tangible goals that are not doomed to clash with the iron laws of politics". Kutney (2014) agrees and asserts that the dominant macro factor is economics. In assessing the leading naions' motives, economic drivers determined the climate policies of most.

Pearse and Böhm (2014) point out that the carbon market failed to deliver its core aim to reduce GHGs. They argue that carbon pricing has functioned as a political barrier to other action: carbon trading is not a "first step" toward broader reform. Instead, it locks in emissions increases and serves as an excuse to abandon other energy policies that make more substantive contributions to decarbonization. Neither the KP nor the EU ETS provide much incentive for long-term low-carbon investment. While it is too early to conclude on the EU ETS, the findings of Pearse and Böhm (2014) are backed up by Sæther (2021), who finds no impact on emissions from the EU ETS. Designing policy instruments to concentrate on the least-cost emission reductions in the short term might be suboptimal in the long term if these reductions lead to locking-in

4 Chapter III. Governance of the framework, Glasgow Climate Pact: 4. The Glasgow Committee on Non-market Approaches is hereby established to implement the framework and the work programme by providing Parties with opportunities for non-market-based cooperation to implement mitigation and adaptation actions in their NDCs.

of carbon-intensive technologies for the next decade (Hepburn, 2007). Lilliestam et al. (2021; 2022) make it clear that the relationship between carbon pricing and decarbonization is complex. While existing carbon pricing schemes have sometimes reduced emissions, they find no evidence that carbon pricing systems have triggered zero-carbon investments, and consistent evidence that they have not. They conclude that the effectiveness of carbon pricing in stimulating innovation and zero-carbon investment remains a purely theoretical argument not backed by empirical evidence.

Keohane and Raustiala (2008) emphasize that effective climate change mitigation requires political commitment. Economists may design strategies to minimize emissions, but this matters little if negotiation results are ambiguous without substantive agreement. These problems cannot be solved without political and institutional procedures by states. Bultheel et al. (2016) claim that climate governance is vital for understanding the failure of the carbon market. The KP produced a constrained climate framework while the PA enabled new avenues for multilateral cooperation on carbon market issues. Institutional inertia has also been key. New market mechanisms and commitments were tabled as the US was planning a federal cap-and-trade market, with an almost tenfold increase in demand for carbon offsets compared to the EU ETS. The delays and downscaling of expectations for carbon market rules and commitments such as cap-and-trade schemes in other industrialized countries are, in part, a response to the failure of legislation on climate change in the US (Reyes, 2011).

Schneider and Stephanie, (2019) identified and narrated the lack of environmental integrity over the pre-steps of the PA. They argue that environmental integrity is a key principle for an effective carbon mechanism. Redmond and Convery (2014) have shown that the KP and post-KP mechanisms shaped fragmented GCM landscapes based on differing approaches. Interest and response vary across groups of countries, and there have been delays in making progress on a unifying framework. Countries finance their carbon pledges domestically. However, for some countries, pledged actions are contingent upon international financing.

Brown (2011) discusses the significance for GCM with respect to Cancun (COP16). His assessment is that climate summits constitute neither a success for nations seeking to reduce their emissions, nor do they put the world on a safe climate path, let alone a just and equitable transition to a sustainable development model. This is because of coalition-building and disagreements among nations. Aklin and Mildenberger (2020) consider domestic politics far more important for success with respect to combating climate change, including the GCM, than international climate treaties. Thus, a lack of multilateralism has led multiple failed attempts to forge a global solution to GCM. Nordhaus (2010) also focuses on the economic aspects post-Copenhagen. His main point is the lack of harmonized carbon taxes, a feature shunned in negotiations among other things because of the US position. Thus, despite over 15 years of high-level UN efforts for binding agreements on emissions reductions, each annual meeting has failed to reach a global agreement.

Rockström et al. (2017) point out that within the PA alarming inconsistencies remain between science-based targets and national commitments towards carbon markets whereas Gills and Morgan (2019) focus on the role of the economic system regardless of the carbon market. There is the tendency for worldwide economic growth to be incompatible with the emissions reductions necessary within the timeframe available to us. In contrast to the literature that evaluates the carbon market by energy and climate variables, the failure of the carbon market can also be seen as an implementation failure of the rules of the PA. Negotiations will only be successful if players can reach consensus on the modalities, procedures, and guidelines that will assist all Parties in complying with their PA obligations. Lázaro-Touza (2016) stipulates contextual factors that can be expected to lead to implementation failure. First, insufficient advances in mitigation commitments compared to the 2°C benchmark and insufficient adaptation finance efforts; second, advances in the competitiveness and deployment of renewable energy; third, unforeseen political events, such as the US Trump Presidency; and fourth, issues between developed and developing countries over allocation responsibilities.

Other research shows that implementing existing pledges according to a robust rule book assisted by market mechanisms had problems. There was divergence between developed and developing countries on the issue of pre-2020 ambitions and on finance (Winkler and Depledge, 2018). Further, Ar6 cooperation and the relationship with NDCs' commitments are exacerbated by a lack of transparency. The main problem is that the Parties are shaping their activities in a way that reflects their national interests in the negotiations (Greiner et al., 2019). The 2019 COP25 was one of the most contentious summits, with Ar6 a major problem. Christoph Bals, policy director of NGO Germanwatch, told Aljazeera (2019) that the continuing conflict about carbon markets, including "the US, Australia and Brazil, where the business model is strongly connected with the fossil fuel industries" had been very visible.

Both Obergassel et al. (2018) and Newell and Taylor (2020) mention two major concerns in the negotiations: First, Brazil was pushing for Article 6.4 emission reductions exports being exempt from corresponding adjustments, while most other Parties rejected this, highlighting that it would lead to double counting. Second, Brazil with Australia, pushed for the trading of Kyoto-era credits, which to most countries was interpreted as promoting measures to use old carbon credits to meet new climate targets. Most deemed this unacceptable (Amaral, 2019). A related argument is that the biggest emitters hampered GCM negotiations. Nicolás (2019), in discussing the failure to agree on Ar6, highlights that beyond Canada and the EU, no major emitters made new, ambitious pledges. Instead of leading the charge for more ambition, the large emitters were "missing in action or obstructive" (Anderson, 2019). Hook (2019) commented that geopolitical tension and the low profile of the US and China severely handicapped carbon market negotiations.

7.2 Three dichotomies

Alternatively, this study proposes a three-stage process using literary analysis to evaluate sections of the literature. The first stage includes the formulation of market-based vs. non-market-based approaches, the development of non-market-based approaches and their transfer to the main objective of this study. The second involves a top-down and bottom-up approach. The criteria that

explain the failure of the carbon market are identified by this approach: binding obligations to reduce emissions and individual states. The failure of international agreements for a legally binding agreement (top-down architecture) has hindered the successful development of the carbon market. The bottom-up approach, on the other hand, consists of a state-specific task force to reduce GHGs. The failure of states to pursue NDC policies has raised the question of the desirability of bottom-up architecture to address GCM, and the IPCC Sixth Assessment Report shows that only 24 countries are actually reducing their emissions. Finally, in the third stage, we look at approaches at the national and international level and what this says about the failure of GCM.

7.2.1 Market-based vs. non-market-based approaches

By market-based approaches we mean CDM, JI, and emissions trading, while non-market-based mechanisms (NMAs) are instruments without internationally transferable units. Here we find the Framework for Various Approaches (FVAs) to promote cost-effective mitigation measures. While FVAs also include market-based approaches, the NMAs can be understood as mitigation activities carried out in one country with voluntary participation and directly accounted for in another country, without issuing internationally transferable units to participants in the mitigation activities. FVAs are needed not only to create an efficient, liquid global carbon market, but also for emerging national carbon markets to function properly. It is difficult for many national carbon markets to be liquid on their own, and a market without liquidity will be dysfunctional and send the wrong price signals. Although not well understood or defined, it is likely to emerge as a key component of GCM (Marcu, 2012a).

Market-based approaches are already well-defined. NMAs are much broader, with very different ideas, and have not yet been defined with principles (UNFCCC, 2012). To Pearse and Böhm (2014), FVAs can be highly efficient by accounting for elements otherwise not included: First, FVAs seek to set rules and guidelines for different approaches to achieving mitigation strategies and policies that reduce and avoid GHG emissions; second, FVAs seek to ensure the environmental integrity of the approaches it covers and address related international issues (e.g., unit transfers or enhanced mitigation ambition); third, FVAs seek to enable the Parties to meet their UNFCCC commitments and targets.

Carbon prices can be categorized as either market- or NMAs and are found in six of the 32 articles. Carbon prices seek to reduce emissions at the lowest possible cost, making them market-based instruments. However, the Parties that negotiated the PA also created a framework for NMA mechanisms focusing on fiscal measures. These are instruments such as imposing taxes to discourage emissions and putting a price on carbon. In this sense, carbon prices are not market-based. These measures are instruments such as levying taxes to discourage emissions and putting a price on carbon. In this sense, carbon prices are not market-based, but NMA. In this article, we consider carbon pricing a special case of market-based instruments.

18 of the 32 articles focus explicitly on market or non-market-based approaches. Market-based constitutes the vast majority, with 16, whereas only two distinct NMAs were identified. The most prominent market-based approaches are Van Kooten (2004), Brown (2011), Dellink et al. (2011), Kutney (2014), Pearse and Böhm (2014), Hawkins (2016), Greiner et al. (2019). For the NMAs, see Winkler and Depledge (2018) and Ecofys and Vivid Economics (2017).

Market-based approaches have been utilized successfully to studying GCM implementation failure. Some studies (McKibbin and Wilcoxen, 2002; Nordhaus, 2010; Pearse and Böhm, 2014) assess KP mechanisms such as carbon prices, CDM, and JI, and confirm that mitigation through the KP mechanisms have substantially influenced the failure of GCM implementation. McKibbin and Wilcoxen (2002) conclude that the KP would force emissions below 1990 levels regardless of the costs and benefits of doing so, while only marginally reducing the rate of warming. Moreover, the KP implied very high prices for emission permits, potentially putting enormous stress on the world trade system. The trade balance for a developed country that imports emissions permits would deteriorate significantly, potentially resulting in increased exchange rate volatility. Thus, some of the explanations above (McKibbin and Wilcoxen, 2002; Pearse and Böhm, 2014) have been an easy way to evaluate GCM implementation failure.

In contrast to market-based studies that suggest mechanisms such as the EU ETS, articles dealing with the PA system have a greater role for non-market approaches such as FVAs. In addition, Ar6 plays a significant role for understanding GCM failure, including article 6.8, which sets up a work program for non-market approaches. These apply to the PA period, where non-market-based approaches are projected to persist beyond the KP mechanism.

In recent years, the problems faced by the KP have encouraged the Parties to explore non-market approach options under Ar6. Parties widely accept that non-market-based solutions are essential post-2020. Thus, what we also see is a movement over time, with non-market-based explanations becoming more prominent.

Among the market-based approaches we identify two main arguments. First, the carbon price and trading system, and second, the KP system. The first main argument focuses on the roles of the carbon trading system. The most cited references are McKibbin and Wilcoxen (2002), Hepburn (2007), Keohane and Raustiala (2008), Nordhaus (2010), Dellink et al. (2011), Pearse and Böhm (2014), Kutney (2014), and Hawkins (2016). Hepburn (2007) states that the market-based approaches from the KP did not increase the scope of emissions trading within the EU ETS to cover more countries, more sectors of companies, and longer time periods, which caused the failure of carbon trading within the GCM. Criticism was raised by the UN bureaucracy over the potential for a possible linking with the EU ETS, and in the US Regional Greenhouse Gas Initiative, which covers emissions from the power sector in the north-eastern United States, and from Australia. Pearse and Böhm (2014) argue that market-based approaches have flawed practices at their core and cannot be reformed: carbon markets can be interpreted as failures in not having delivered on their main objective, to reduce GHGs.

The second main argument focuses on the KP system. Schiermeier (2012) asserts that climate treaties must take a more pragmatic approach than the KP. Market-based approaches had inequitable carbon targets within the KP and failed to win over the biggest polluters because they relied on a mix of ethical and

environmental rationales rather than economic ones. Benessaiah (2012) explains that the KP market-based approaches were not carefully designed to evolve along with GCM and the dynamic social-ecological systems. Market-based mechanisms and voluntary carbon markets require enabling and connecting institutions. . .while remaining flexible to rapidly changing social-ecological systems" (Benessaiah, 2012, p. 4). Greiner et al. (2019) specify that carbon markets therefore remain in limbo, with the KP mechanisms having lost their incentive function. Some studies focus on the role of countries. Nordhaus (2010) highlights how problems for GCM implementation arose because the Kyoto and Copenhagen regimes adopted cap-and-trade structures. Cap-and-trade would for instance require globally designed environmental policies with most countries contributing. The rich countries would need to bring along the poor, the unenthusiastic, and the laggards with the necessary carrots and sticks to get all on board.

Regarding NMAs, Winkler and Depledge (2018) argue that after over 170 countries with officially registered NDCs adopted the PA, we know that even if all formulated NDC targets are met, temperatures will still rise almost 3°C. The PA has also been shaken by incidents such as the 2016 election of Donald Trump as US president and news that the Trump administration would 'cease all implementation' of the PA and withdraw from the treaty. COP23 (2017) explains that the actors are unable to reach consensus on modalities, procedures and guidelines that will assist all Parties in complying with their PA obligations, including GCM. Postponing critical decisions until later COPs was not good, as momentum for implementation, including GCM, must be maintained (COP23, 2017).

Of the academic fields that have dealt with the failure of GCM implementation, two stick out: climate politics and economics. Four articles (McKibbin and Wilcoxen, 2002; Hepburn, 2007; Pearse and Böhm, 2014; Hawkins, 2016) are within the field of climate politics, with five (Van Kooten, 2004; Nordhaus, 2010; Dellink, Briner and Clapp, 2011; Bultheel et al., 2016; Ecofys and vivid Economics, 2017) from economics. For the NMAs, the footprint of economists is naturally smaller. Here the focus has rather been on analysing climate policy and climate negotiations, primarily by political scientists.

7.2.2 Top-down vs. bottom-up approaches

We define top-down approaches as attempts at imposing overarching, mutually binding frameworks for emissions reductions from major international conferences, whereas bottom-up refers to emissions reductions efforts primarily initiated and monitored by individual states. Of the 32 articles, we classify 15 as top-down, and 17 as bottom-up.

The top-down approach is embodied in the KP with its emphasis on creating binding commitments. For effective reductions, this approach brought specific enforcement mechanisms such as cap-and-trade and carbon prices. Bottom-up approaches can be identified primarily from the PA onwards, such as NDCs and Ar6. Both were new GCM measures established through the PA. Ar6 provides the opportunity for states to cooperate on a voluntary basis when implementing NDCs. The PA created a long-term future for carbon markets through Ar6. Stua et al. (2022) argue that the PA, through Ar6, provides the legal framework for the creation of international regulations to govern the carbon market through a GCM. Ar6 international market-based provisions and mechanisms, in conjunction with domestic market-based policy instruments, are poised to play a central role in delivering the NDCs of many countries. Ar6 and the NDCs contribute to the development of criteria and mechanisms for mitigation, which reflect the growing change for addressing climate change impacts, including GCM. Such ideas have been derived from the post-KP or PA periods. Thus, there is a clear historical development in the sense that the KP with subsequent efforts were mostly top-down, while bottom-up efforts have become dominant since the PA. Bottom-up approaches are now dominant in dealing with GCM.

Top down-explanations are found with McKibbin and Wilcoxen (2002), Van Kooten (2004), Hepburn (2007), Keohane and Raustiala (2008), Nordhaus (2010), Dellink et al. (2011), Cozier (2011), Brown (2011), Schiermeier (2012), Pearse and Böhm (2014), Kutney (2014), Bultheel et al. (2016), Lázaro-Touza (2016), Hawkins (2016), and Greiner et al. (2019). These 15 explanations are primarily connected to the KP system. Van Kooten (2004) argues that the protocol will fail to solve the GCM issue because it has too many loopholes, inadequate governance structures, and insufficient compliance provisions, and that most countries will be unable to meet their own Kyoto obligations. Or, if they do, the costs of compliance for GCM will be unacceptably high. Most states have less incentive to sign up for any future international agreements because current policies do little to reduce emissions and avert global warming (Van Kooten, 2004). To further support this argument, Rosen (2015) argues that the KP is a clear case of institutional failure, as the short timeframe for action, the binding targets, the emission reduction measures and the provisions for future commitment periods have led to short-sighted behaviour by member states. For another top-down explanation, see Bultheel et al. (2016), who state that GCM failed as part of the KP because in real life the flexibility mechanisms revealed limitations as political and economic tools, even if they shaped and implemented an international emission trading system of carbon for states.

In contrast, bottom-up explanations focus on how the lack of integration and disagreement between countries have led to the failure of GCM. Of the 32 pieces of literature, such arguments are found in Rockström et al. (2017), COP23 (2017), Ecofys and Vivid Economics (2017), Winkler and Depledge (2018), Amaral (2019), Obergassel et al. (2018), Aljazeera (2019), and Streck et al. (2019). One strand of literature emphasizes that negotiators have not managed to find common ground across negotiation items ranging from mitigation action to ensuring transparency and follow-up, including "global stock takes," climate finance and technology transfer. The Paris rules may prove more robust and sustainable than those of the KP in building on accountability, trust, and compliance for GCM (Streck et al., 2019).

Five of the 15 top-down studies are from the field of economics. In contrast, the bottom-up approaches tend towards political science and law, focusing on climate policy (Rockström et al., 2017; Obergassel et al., 2018; Winkler and Depledge, 2018; Amaral, 2019), climate change and economics (Ecofys and Vivid Economics, 2017; Aljazeera, 2019; environmental law (Streck et al., 2019), and international relations and geography (Newell and Taylor, 2020).

7.2.3 National level vs. international level approaches

The final lens through which we analyse GCM implementation failure, is national vs. international level. This extends from among

other things the role of the USA and its leadership/lack of leadership, through international climate change negotiations and agreements, to the international level. Disagreements between developed and developing countries (China, India, and Brazil the foremost) constitute one main branch of examples on the international level. Nicolás (2019) argues that almost 200 countries failed to agree on Ar6. Nicolás (2019) also notes that while the EU (except Poland) and Canada has committed to climate neutrality by 2050, until recently, no other big emitters had made similar pledges. And China, India, and smaller developing states are demanding economic support from wealthy states to finance climate goals.

27 of the 32 studies are at the international, with only five at the national level. However, these five all occur towards the end of our time-period. Compared to the KP and post-KP, the PA and post-PA period represents a clear development and change in approach. Moving away from KP emission mechanisms such as IET, JI, and CDM–all international level mechanisms–scholarship on the PA and post-PA period relies on individual national targets such as NDCs for GHG mitigation. The GCM literature exhibits two main international level explanations: The KP system; and disagreements between developed and developing states. Among the first we count McKibbin and Wilcoxen (2002), Van Kooten (2004), Keohane and Raustiala (2008), Dellink et al. (2011), Schiermeier (2012), and Redmond and Convery (2014). McKibbin and Wilcoxen (2002) argue that the principal international policy instrument of the KP should be a system of internationally tradable emissions permits. They emphasize that a main problem with the KP, however, is that no individual government has an incentive to police the agreement.

The second strand of international level explanations focuses on disagreements between developed and developing states. Brown (2011) focuses on the failure of developed nations to reduce greenhouse gases. Brown believes that developed nations must take more ethically responsible positions on an urgently needed global climate change solution.

On the national level we find Hepburn (2007), Hawkins (2016), Winkler and Depledge (2018), Aljazeera (2019), and Newell and Taylor (2020). These authors focus on the role of specific states. Newell and Taylor (2020) argue that the problem of reducing GHGs based on GCM can be traced back to politicians. We had a conjuncture where presidents Trump in the US, Bolsonaro in Brazil, Putin in Russia, and Prime Ministers Modi in India, Morrison in Australia, and Johnson in the UK all either doubted the scientific basis of climate change, or actively sabotaged more aggressive action to address it. Newell and Taylor (2020) believe that a broader geopolitical and economic context of right-wing populism, deepening marketization, and financialization of responses to climate change are of relevance to the GCM issue.

On the international level the field of economics dominates, with Van Kooten (2004), Nordhaus (2010), Pearse and Böhm (2014), Ecofys and Vivid Economics (2017) as the main contributors; followed by policy (e.g., Keohane and Raustiala, 2008; Redmond and Convery; 2014; Rockström et al., 2017; Obergassel et al., 2018), ethics (Brown, 2011), and science and technology studies (Cozier, 2011). On the national level we find economics articles (Aljazeera, 2019); policy articles (Hepburn, 2007; Hawkins, 2016; Winkler and Depledge, 2018); and international relations, and geography articles (Newell and Taylor, 2020).

8 Summary

Integrating the three dichotomies and adding the substantive arguments about GCM implementation failure, we can summarize them into one system-level and one state-level argument: On the system level many scholars focus on the KP and its mechanisms, i.e., the emissions trading system, JI, and CDM, whereas on the state level, the main arguments centre around the lack of integration and on disagreements between countries. The most critical arguments on the KP system and its mechanisms have received much attention (e.g., McKibbin and Wilcoxen, 2002; Van Kooten, 2004; Hepburn, 2007; Nordhaus, 2010; Benessaiah, 2012; Schiermeier, 2012; Pearse and Böhm, 2014; Bultheel et al., 2016; Amaral, 2019; Greiner et al., 2019). These arguments have changed only slightly since the KP, for three main reasons: First, the KP does not have a flexible mechanism and most countries will be unable to meet their own Kyoto obligations (Van Kooten, 2004). Second, other studies provide additional arguments on GCM failure. Both Benessaiah (2012) and Bultheel et al. (2016) confirm the results from earlier and the problems of the KP system and its mechanism. Benessaiah (2012) singles out the governance system within the KP. She argues that the KP carbon markets are not designed to carefully evolve along with a dynamic social-ecological systems, but that they need enabling and connecting institutions. Third, Bultheel et al. (2016) assess the compatibility of the commitments under the KP. Cost-effective low-carbon transition was not the intention of the KP. The constrained climate framework advocated by the KP is the essential element in GCM failure.

In another sense, with the PA and its emphasis on NDCs, the field has moved away from this first group of arguments towards the second most frequent argument in the literature: Focusing more on the state and less on the system, integration and disagreement between countries is crucial to how the literature now understand the failure of GCM implementation (e.g., Keohane and Raustiala, 2008; Kutney, 2014; Hawkins, 2016; COP23, 2017; Ecofys and Vivid Economics, 2017; Schneider and Stephanie, 2019; Obergassel et al., 2018; Streck et al., 2019; Nicolás, 2019; Anderson, 2019). In the words of Hawkins (2016: 20): "While these initiatives, as well as Article 6, are certainly crucial for laying the political and technical foundations for carbon market clubs, they need to be complemented by more dedicated and focused efforts. The EU, New Zealand, South Korea, and Switzerland, as well as Canada and the subnational US schemes, are currently the most likely candidates for initiating a carbon market club." Obergassel et al. (2018) argue that lack of cooperative action under Ar6 is the reason for GCM implementation failure. The obstructive power of a handful of countries delays and blocks the process, even overturning the PA to move in a direction with far less ambition. To Streck et al. (2019) GCM failure is associated with a lack of accountability, trust, and compliance between countries. Countries did not manage to find common ground across negotiation items ranging from mitigation action to ensuring transparency and follow-up, including "global stocktakes," climate finance and technology transfer. Moreover, developing countries did not receive enough assistance to comply.

Finally, we simultaneously apply the dichotomies. First, we present three two-by-two matrices to show how the different

TABLE 2 Three dichotomies organized according to three two-by-two matrices.

	Top-down	Bottom-up		International	National		International	National
Market	14	2	Market	14	2	Top-down	14	1
Non-market	0	2	Non-market	1	1	Bottom-up	13	4

dichotomies can be paired. Only 18 of the articles were easily placed along all the three dichotomies, thus the figures in the matrices vary. They do however leave a general impression of a field where market explanations dominate, as do international level approaches (Table 2).

Of the 18 easily placed articles, one combination stands out. Articles that combine a market-focus, a top-down approach, and an international level focus account for 13 out of 18. Here we emphasise McKibbin and Wilcoxen (2002), Van Kooten (2004), Keohane and Raustiala (2008), and Kutney (2014) as typical of the entire literature. Keohane and Raustiala (2008:1) argue that "the difficulties of negotiating national emissions quotas, coherently linking national regulatory systems, monitoring implementation, avoiding renegotiation, and ensuring compliance with international commitments" can be seen as the main problems. These cannot be solved together without the political commitment and willingness of heads of state to bear the necessary costs.

This is a review article; thus, our goal is not to provide personal assessments of the articles and arguments analysed. We do however think that one substantive argument shines through, and we find ourselves in agreement with it. Thus, along with major parts of the literature, we suggest that the failure of GCM implementation at the UNFCCC negotiations is due to countries at the state level "not aiming high" when it comes to national regulations, building regulations and policies, i.e., regulatory and economic instruments to reduce GHGs–leading to a certain amount of fatigue. In terms of climate negotiations, too many have perceived of GCM as a "small potato". On the international level, this requires the biggest emitters to exercise "coercive power" in the international negotiations. This, they have been reluctant to do. Thus, GCM has been caught between the lack of domestic effort at the state level and a lack of external pressure from the biggest actors at the international level.

9 Conclusion

GCM has been an issue since before the very first COP meeting and has seen various developments since the KP. GCM has been at the heart of the carbon neutrality concept, as achieving net-zero carbon dioxide emissions can be done through removal or offsetting. Disagreements between developed and developing countries about joint implementation for reducing GHGs was an issue already at the outset. The compromise that was made was that a pilot phase would be started, during which projects were referred to as Activities Implemented Jointly. This continued for the KP and post-KP. During this stage, GCM experienced the establishment of new mechanisms, such as IET and CDM, for achieving the KP objectives. States with KP commitments (Annex B Parties) accepted targets for limiting or reducing emissions. IET, as set out in Article 17 of the KP, permits Parties with emission units to spare to sell their excess capacity to states that are over their targets. In addition, CDM is a part of emission reduction targets under the KP, which allows emission-reduction projects in developing countries to earn CER credits. IET and CDM constitute a summary of how GCM is meant to assist countries to obtain their emission targets under the KP.

In seeking to organize the explanations for the failure of GCM implementation, we employed three dichotomies as organizational tools; market-based vs. non-market based, top-down vs. bottom-up, and national vs. international. From the COP1 onwards, including the KP and the PA, GCM has remained an issue with little consensus. There is a plethora of arguments why GCM has failed. What is striking is that when combining the three dichotomies, one combination contains the overwhelming majority of articles, namely, market-based, top-down, and international. What is however also striking is that this is countered by a historical trend away from top-down and towards bottom-up approaches since the PA. This is unlikely to change. There is also a possible trend away from market-based towards non-market-based solutions. COP26 may have brought us closer to a resolution on GCM, but for now GCM remains an important but throughout a period of more than 25 years unresolved component of the climate policy puzzle.

This study obviously has limitations. First and foremost, negotiations under the UNFCCC are continuously ongoing. Thus, we cannot provide a final answer as to the failure of GCM implementation. Each year we observe small steps and changes in terms of regulation and policy making. This is an ongoing process with no defined or declared end point, with new data arriving every year. This does however not take away from the usefulness in providing an assessment of GCM, based on where we stand today. The failure of GCM implementation reveals the complexness of climate negotiations. For instance, after more than 2 decades, non-market-based approaches (NMAs) are still being discussed in the UNFCCC negotiations, as part of Ar6, without any decision having been made. Thus, NMAs are still not taken seriously enough to be genuinely pursued by countries under the UNFCCC. At COP28 in Dubai there was only a slow discussion between countries on the text for voluntary carbon markets. This "carbon market blockage" makes it difficult to move forward with the implementation of GCM. There is much to suggest that there are major polluters, such as China and India that oppose the idea and nature of carbon markets and whose emissions and national policies are not compatible with carbon market mechanisms to achieve climate targets. This has led other major parties, such as the EU and the US, to also not be very

motivated to pursue GCM. If COP29 in Azerbaijan and COP30 in Brazil lead to more transparency and clearer guidelines for Ar6.4 rules and to a formal function for Ar6.4 and non-market-based approaches, this will signal welcome progress for the implementation of GCM.

Irrespective of this review, we believe that future research on carbon market policy and negotiations ought to focus more on the analysis of voluntary carbon market agreements–a crucial tool for mobilizing climate finance for climate action–as well as the negotiating texts of Ar6.4 and NMAs and the definitions used by parties to define and clarify them, to formally progress and implement GCM.

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Has bank digitization facilitated green transformation of enterprises?

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Based on measuring the green transformation of heavily polluting enterprises based on the sub-dimensions of green strategy and green action, we empirically analyze whether and how bank digitization affects the green transformation of enterprises by using the data of China's A-share heavily polluting enterprises from 2010 to 2021. The findings show that 1) bank digitization has a significant positive effect on firms' green transformation; 2) bank digitization promotes firms' green transformation by alleviating firms' financing constraints and improving firms' ESG performance; 3) governmental environmental regulations and media attention positively moderates the relationship between bank digitization and firms' green transformation; and 4) bank digitization is more likely to promote the green transformation of firms that are highly digitized, non-state-owned firms, and enterprises in the eastern region; 5) the sub-dimension test shows that bank digitization has significant differences on different dimensions of green transformation. The above analysis shows that bank digitization should be deeply integrated with the green transformation of enterprises, and the former should be deeply embedded in supervising, forcing and empowering enterprises to upgrade environmental protection technology and sewage treatment, and the regulator should formulate a more detailed environmental protection disclosure program to realize the consistency "words" and "deeds" of the green transformation of enterprises.

KEYWORDS

digital transformation, green transformation, heavy polluters, financing constraints, ESG performance

1 Introduction

Since the Industrial Revolution, economic growth has led to serious environmental problems (Lee and Lee, 2022; Lin and Ma, 2022), and how to cope with environmental problems and make a green transition has become a difficult problem to solve all over the world (Zhao et al., 2022). As the world's largest carbon emitter and energy consumer and the second largest economy, China plays an important role in alleviating the contradiction between economic development and resources and the environment (Zhai and An, 2020). In the face of the urgency of environmental governance, and to guarantee the sustainable development of the economy and the ecological environment, China is pursuing a green transformation while ensuring economic growth (Zhao et al., 2022). Promoting the greening and decarbonization of economic and social development is a key part of achieving high-quality economic development, and an issue that the Chinese government and enterprises need to focus on (Wang L. et al., 2022). Thus, the green transformation of enterprises, especially heavily polluting enterprises, is a necessary part of

high-quality development and should be embedded in the greening and decarbonization process of social development. Enterprises are an important engine of economic development and are the main actors in pollution prevention and ecological civilization (Shrivastava, 1995; Liu et al., 2022).

Finance, as the bloodline of the real economy, is undergoing systemic digital transformation, taking on the important responsibility of green transformation of enterprises and promoting high-quality economic development (Cao et al., 2022; Liu et al., 2022; Ma et al., 2023). The digital economy has demonstrated its strong resilience and potential in the face of environmental problems (Hao et al., 2023), promoting changes in production and governance and effectively driving high-quality green development (Zhang and Liu, 2022; Wu et al., 2023). In the digital context, the phenomenon of financial disintermediation has become more serious, competition in the financial services industry has intensified, and financial institutions have to undergo digital transformation to adapt to the overall environment (Gomber et al., 2018; Lin and Ma, 2022). In this regard, the Chinese government is fully aware of the importance of fintech development and actively promotes the digital transformation of financial institutions. China's financial industry has always been significantly bank-led (Allen et al., 2005; Zheng et al., 2023), and the digital transformation of banks is the main body of the digital transformation of financial institutions. 2023 The People's Bank of China (PBC) even released the "Specification for Digitalisation Models of Inclusive Financial Services in the Banking Sector" in July 2023, which regulates the digitalization models of the banking sector and accelerates the digital transformation process of the banking sector. Transformation process. Some scholars believe that banks reduce operating costs, simplify business processes, improve service efficiency, alleviate financing constraints of enterprises, and correct resource mismatch through digital technology (Gomber et al., 2018; Lin and Ma, 2022; Tan et al., 2023). However, some scholars believe that the digitalization of China's banking industry is currently at the stage of simple application of digital technology, and the existing business model is not yet able to portray customer profiles well enough to accurately assess customer credit and risk levels (Feng et al., 2022; Murinde et al., 2022), and cannot effectively provide credit support for the green transformation of enterprises. At the same time, various types of banks are differentiated in the process of digital transformation (Xie and Wang, 2023), and the stability of diversified banks deteriorates with digital transformation (Khattak et al., 2023), as well as the impact on the cost of credit for different types of enterprises (Lyu et al., 2023). B bank digital transformation presents both opportunities and challenges for banks. So, can banking and digitalization facilitate the green transformation of heavy polluters? What is the mechanism by which bank digital transformation promotes the green transformation of heavy polluters? This is a typical empirical question.

Taking an overview, past studies have mostly explored how to promote corporate green transformation from the perspectives of government subsidies (Wu and Hu, 2020), environmental regulation (Wang L. et al., 2022), and corporate governance (Galbreath, 2019). Although some scholars have noted that digital financial development is expected to achieve green economic growth (Hao et al., 2023), they have more often explored the impact of digital finance on the green innovation dimension of enterprises (Feng et al., 2022; Liu et al., 2022), and have not comprehensively measured the impact of digital financial development on the overall green transformation of enterprises. In addition, few existing studies have brought the study of digital finance on corporate green transformation down to the level of banks' digital transformation, and more often cover banks' digitization within digital finance as a whole (Lin and Ma, 2022; Ma et al., 2023). Relative to previous studies, this paper expands the research on the consequences of banks' digital transformation, extends the impact of banks' digital transformation to the green transformation of heavily polluting enterprises, provides new evidence for the positive externality effect of banks' digital transformation, and provides theoretical and empirical support for accelerating banks' digital transformation based on the novel perspective of the green transformation of heavily polluting enterprises.

2 Theoretical analysis and research hypothesis

The green transformation of enterprises has strong externalities, a long cycle, and a large demand for funds (Cao et al., 2021; Lv et al., 2023), and enterprises' inputs are unable to satisfy the funding gap of green transformation, so external financing has become an important channel for obtaining funds for the green transformation of enterprises (Liu et al., 2022; Guo et al., 2023). Traditional financial institutions are poorly inclusive and tend to favor low-risk and short-term projects, making it difficult to provide stable financial support for corporate green transformation (Feng et al., 2022). Digital finance relying on digital technology is efficient and convenient (Gomber et al., 2018; Tan et al., 2023), providing important support for corporate green transformation. Bank digitalization is the mutual integration of digital technology and traditional banks (Guo et al., 2020; Zhu and Jin, 2023). To crack the resource, environment, and climate problems faced by the development of human society, digital technology is deeply rooted in green attributes from its birth. The green attributes of digital technology and the nature and mission of financial services for the high-quality development of the real economy are embedded in the green transformation of enterprises in the development of digital finance (Ozturk and Ullah, 2022). It has been shown that digital finance promotes the improvement of corporate green innovation and the reduction of environmental pollution through the optimization of credit allocation and regulation (Gomber et al., 2018; Liu et al., 2022; Lin and Ma, 2022). Chinese finance is characterized by significant bank dominance (Allen et al., 2005; Zheng et al., 2023). The digital transformation of banks will further break down the information barriers between banks and enterprises (Rodrigues et al., 2022), The quantity, quality, depth, breadth, and speed of information of banks and enterprises will be significantly improved, and the pricing bias, supervision bias, and risk control bias of bank credit will be further reduced, the abuse of power by bank management will be restrained, and the screening and supervision of green projects will become more scientific and precise, which in turn can empower enterprises to green transformation (Gomber et al., 2018; Murinde et al., 2022; Li M. et al., 2023).

Based on the above analyses, this paper proposes the following hypotheses:

H1: Digital transformation of banks empowers green transformation of enterprises.

The origin of banks' digital transformation lies in serving the real economy, the symbiosis and co-creation of value between banks and the real economy (Berger et al., 2020), and the existence of the value of bank franchises that make banks' concessions to enterprises possible. 1) In recent years, China's demographic dividend has continued to decline and labor costs have been rising (Zhou et al., 2023). The digital transformation of banks promotes the shift of banking services from offline to online, and a large number of repetitive tasks originally performed by humans are mostly replaced by machines, with business processes automated and unmanned, which reduces the labor demand of banks, lowers labor costs (Berg et al., 2022), and brings about a scale effect. 2) Enterprises have been digitally transformed to improve their performance (Peng and Tao, 2022), Based on the digitization of business operations, banks use new technologies such as big data and artificial intelligence for pre-credit review and post-credit supervision, to enhance the screening capacity of banks' information screening ability and the screening capacity of enterprises' green behaviors, and to carry out real-time tracking of the use of enterprises' funds, to reduce the risk management costs of banks' green credits (Gomber et al., 2018; Guo et al., 2023), effectively driving down bank costs and improving operational efficiency. 3) In the context of the digital transformation of banks, the network characteristic of traffic is king is increasingly prominent, and concessions to enterprises are an important means of increasing customer stickiness, improving customer experience, cultivating customer habits, and exploring new customer needs.

Based on the above analysis, this paper proposes the following hypothesis:

H2: Banks' digital transformation promotes banks' concessions to enterprises, eases enterprises' financing constraints, reduces enterprises' green transformation risks, and thus leads to enterprises' green transformation.

In the digital era, the degree of enterprise digitization is increasing year by year (Peng and Tao, 2022), along with the deepening of the online presence of enterprises' green business data, social responsibility, and corporate governance information (Wang and Esperança, 2023), and the "digital footprint" and "digital portrait" of the enterprise's sustainable operations can be quickly and accurately captured by banks. The "digital footprints" and "digital portraits" of enterprises' sustainable operations can be quickly and accurately captured by banks. The information asymmetry between banks and enterprises before lending is significantly reduced, and the subjectivity in traditional credit approval is significantly alleviated (Berg et al., 2022). As the degree of transparency and standardization of bank-enterprise information increases, banks are also better able to monitor the flow of loans and alleviate post-loan information asymmetry between banks and enterprises (Gomber et al., 2018; Li M. et al., 2023). More importantly, ESG ratings of firms by professional organizations connect firms to the market, improve firms' external information (Fang et al., 2023), and further reduce the information asymmetry between firms and banks. With the improvement of the efficiency and quality of information communication between banks and enterprises, banks can capture corporate ESG performance faster and more accurately, and the demand for corporate ESG performance increases (Zhang, 2023). Corporate ESG data effectively plays the role of market incentives and external monitoring mechanisms (Fang et al., 2023), which will continue to tighten credit approval for polluting projects with low ESG ratings and contrary to national policies, forcing enterprises to transform green production and reduce corporate pollution.

Based on the above analysis, this paper proposes the following hypothesis:

H3: Banks' digital transformation improves firms' ESG performance and forces firms to undergo green transformation.

Government environmental regulation is a formal system that constrains firms' environmental pollution behavior, forcing firms to increase their green investment and make a green transition (Wang L. et al., 2022). Enterprises subject to looser environmental regulations do not take the initiative to go green based on concerns about production costs, and strict government environmental regulations increase enterprise costs, reduce enterprise revenues, and incentivize enterprises to go green (Cai et al., 2020). Government environmental regulation incorporates corporate environmental governance into the economic and social rating system for high-quality development, using the government's "hand" to support sustainable development (Wang L. et al., 2022). In the era of the digital economy, the increase in the intensity of government environmental regulation can help enterprises improve factor allocation efficiency (Cao et al., 2021) and effectively use the funds provided by banks' digital transformation; at the same time, the greater the intensity of government environmental regulation, the greater the impact of ESG ratings on banks' credit decision-making (Zhang, 2023), which can effectively promote banks' digitalization to improve the performance of enterprises' ESG, and thus promote enterprises' green transformation. Improvement, thus promoting the green transformation of enterprises.

Based on the above analyses, this paper proposes the following hypothesis:

H4: The increase in the intensity of government environmental regulation will strengthen the role of banks' digital transformation in facilitating the green transformation of enterprises.

Media attention pairs are informal institutions that complement government environmental regulation (Jie and Jiahui, 2023). Media attention is the main external supervisor and information intermediary, on the one hand, the media increases the transparency of corporate information through tracking and reporting on enterprises, and increases the difficulty and cost of corporate environmental violations (Li Z. et al., 2023); on the other hand, with the continuous improvement of the public's awareness of environmental protection, the media reports have become an important channel for the public to understand the information on corporate environmental governance and condemn corporate pollution, increasing the possibility of government regulatory intervention, and the related negative reports affect the value and

reputation of enterprises (Zhu and Jin, 2023). Likelihood of government regulatory intervention and related negative reports affecting firms' value and reputation (Zou et al., 2015; Wang F. et al., 2022), further increasing public and bank scrutiny of environmental governance issues and supervising firms' management to adopt green strategies (Wang F. et al., 2022). Therefore, the higher the media attention, the greater the contribution of bank digitalization to corporate green innovation should be.

Based on the above analyses, this paper proposes the following hypothesis:

H5: Increased media attention reinforces the role of banks' digital transformation in promoting green innovation in companies.

3 Research design

3.1 Sample data source and processing

This paper selects Chinese A-share listed heavy polluting enterprises as the research sample. For the selection of heavy polluting enterprises, this paper firstly relies on the Guidelines on Environmental Information Disclosure for Listed Companies (Draft for Public Comments) issued by the Ministry of Ecology and Environment (former Ministry of Environmental Protection) in 2010 to categorise 16 types of industries, such as thermal power, iron and steel, cement, etc., as heavy polluting industries, and then combines with the Guidelines on the Classification of Listed Companies by Industry (2012) of the Securities and Exchange Commission to select 20 industries initially, including non-metallic mineral mining and processing, wine, beverage and refined tea manufacturing, etc. and other 20 industries. Finally, with reference to the selection of heavy pollution industries by He et al. (2022), 13 industries including coal mining and washing industry, oil and gas extraction industry are screened out, which include: B06, B07, B08, B09, C17, C19, C22, C28, C29, C30, C31, C32, D44. The digital financial data of the Digital Finance Research Centre of Peking University used in this article Research Centre's commercial bank digital transformation data timeframe is 2010–2021, so this paper selects A-share heavy polluters from 2010 to 2021 as the research object.

The sample data are processed as follows: 1) ST and *ST enterprises are excluded; 2) samples with missing data are excluded. A total of 212 enterprises were obtained for 12 years of observations, and finally 2,372 sample observations were obtained. The financial data and news report data in this paper come from CSMAR database, green patent data from CNRDS database, enterprise annual reports from Juchao Information Network, and ESG performance data from CSI ESG Rating.

3.2 Variable definition

3.2.1 Explained variables

The explanatory variable in this paper is corporate green transformation, which is obtained by crawling the annual reports of enterprises using Python software. Firstly, referring to Li and Wang (2021) and Wu and Li (2022), the search direction of enterprise green transformation is divided into "enterprise green strategic transformation" and "enterprise green action transformation," in which the strategic transformation is further divided into two dimensions (strategy The strategic transformation is divided into two dimensions (strategy, planning), and the action transformation is divided into three dimensions (environmental technology upgrading and transformation, sewage treatment, monitoring and prevention). Secondly, based on the Guiding Opinions of the State Council on Accelerating the Establishment of a Sound Green, Low-Carbon and Circular Economic System and the China Green Transformation and Sustainable Development Report, the key words of each dimension were identified; then Python software was used to read the annual reports of enterprises, and the total number of word frequencies of key words appeared in the annual reports of the enterprises was counted, and logarithmic processing was carried out to measure the degree of green transformation of the enterprises. The larger the value of enterprise green transformation, the stronger the degree of enterprise green transformation.

3.2.2 Explained variables

The explanatory variable of this paper is the bank digital transformation index, which indicates the degree of commercial banks' digital transformation of corporate lending. 1) The degree of commercial banks' digital transformation is measured by the Peking University Commercial Bank Digital Transformation Index, which breaks down banks' digital transformation into three sub-dimensions: strategic digitalization, business digitalization, and management digitalization; and 2) the level of corporate lending from banks is measured by referring to the study of He et al. (2023) in conjunction with the ratio of the total amount of bank loans obtained by each enterprise to the total assets each year. The weighted average level of commercial banks' digital transformation of corporate loans is then calculated based on the level of corporate loans.

3.2.3 Mechanism variables

3.2.3.1 Firm financing constraints (FC_SA)

In this paper, the SA index is used to measure the financing constraints faced by firms, and the SA index is constructed using two relatively exogenous variables, namely, firm assets, and age. The SA index is calculated as follows:

$$SA = -0.737Asset + 0.043Asset^2 - 0.004Age$$

where Asset is the natural logarithm of the firm's total assets and Age is the firm's year of establishment. a negative SA index and its larger absolute value indicate that the firm is subject to a more severe degree of financing constraints.

3.2.3.2 ESG performance (ESG)

Currently, the ESG rating systems for Chinese companies mainly include CSI, BDRC, Bloomberg, etc. Among them, the CSI ESG rating system refers to the international mainstream ESG evaluation framework, integrates Chinese characteristics, and covers more companies. Among them, the CSI ESG rating system refers to the international mainstream ESG evaluation framework, integrates Chinese characteristics, and covers more enterprises, so this paper uses the CSI ESG rating data as a measure of corporate

ESG performance, according to the CSI ESG ratings from high to low assignment of value, the highest score of 9 points, the higher the score indicates that the better the performance of corporate ESG.

3.2.3.3 Government environmental regulation (ER)

Referring to the studies of Zhang and Chen (2021) and Pei et al. (2019), this paper firstly selects 27 environmental vocabularies by considering the three aspects of environmental protection goals, environmental protection objects, and environmental protection measures; secondly, it downloads the working report of each prefectural and municipal government, reads the working report of each prefectural and municipal government by using the Python software, subdivides the word frequency of the text of each prefectural and municipal government's working report, and tallies the environmental Finally, the ratio of the word frequency of environmental words to the word frequency of the full text of the municipal government work reports was used to measure the intensity of environmental regulation by the municipal government at each prefecture level. The larger the value, the stronger the government's environmental regulation. The intensity of government environmental regulation for each enterprise is matched according to the city to which the enterprise belongs.

3.2.3.4 Media attention (LNMEDIA)

With the arrival of the digital era, traditional paper media received the influence of new media, the living space is constantly compressed, and more and more traditional paper media due to the deterioration of economic efficiency choose to suspend publication. In comparison, online media has the advantages of stronger timeliness, longer retention time, more openness, and lower cost. Considering this, the influence of online media is greater than that of traditional paper media in the context of the digital economy, so this paper measures the media attention received by companies based on the online news coverage of listed companies in CNRDS. At the same time, existing studies have found that negative media coverage receives more public attention and exerts more pressure on heavily polluting companies than positive coverage. This is mainly because negative media coverage will lead to damage to the firm's reputation and make investors question the competence of the firm's management. Therefore, negative media reports are an important monitoring channel for the green transformation of heavily polluting enterprises. Therefore, this paper measures the media attention received by firms based on the total number of negative online media reports of listed firms in the CNRDS.

3.2.4 Control variables

In order to avoid the possibility of biased econometric tests due to omitted variables, this paper refers to the studies of Liu et al. (2022) and Li et al. (2022) and selects the following control variables: return on total assets (ROA), financial leverage (Lev), two rights (Dev), proportion of sole directors (Inde), firm size (Size), top ten shareholders' shareholding (Top10), and firm age (AGE). In order to minimize the endogeneity problem, the paper further controls for two macro-level variables: provincial GDP growth rate (GDPg) and provincial consumer price index (CPI).

Table 1 is a description of the main variables in this paper.

3.3 Descriptive statistical analyses

Table 2 reports the results of descriptive statistics for the main variables. As can be seen from Table 2, the mean value of Green Transformation of Enterprises (GTS) is 5.09, the minimum value is 0, and the maximum value is 13.24, which indicates that there is a difference in the degree of green transformation among enterprises. The two sub-dimensions of enterprise green transformation, green strategy transformation (Strategy) and green action transformation (Action) have a minimum value of 0 and a maximum value of 6.11 and 9.01, respectively, indicating that there is a gap between them. The mean value of the Total Digital Transformation Index (TDI) for banks is 13.17, with a minimum value of 0 and a maximum value of 61.05, indicating a large gap in the digital transformation of bank-to-business lending among firms. Among the sub-dimensions of banks' digital transformation, the Management Dimension (MDI) has the largest mean value, which is much higher than Strategic digitalization (SDI) and Business digitalization (BDI).

3.4 Model construction

$$GTS_{it} = \alpha_0 + \alpha_1 DI_{it} + \alpha_2 Control_{it} + \mu_i + \delta_t + \varepsilon_{it}$$

In model (2) i denotes the enterprise and t denotes the year. Where GTS is the degree of green transformation of the enterprise, and specifically the enterprise green transformation is divided into the following two dimensions: Strategy denotes the enterprise green strategy transformation, and Action denotes the enterprise green action transformation. DI is the bank digital transformation index, and specifically, the bank digital transformation index includes the following four dimensions: SDI denotes the bank strategic digital index, BDI denotes the Bank Business Digitalization Index, MDI denotes the Bank Management Digitalization Index, and TDI denotes Total Bank Digitalization Index. Control is a vector composed of control variables. μ_i denotes individual fixed effects, controlling for individual-level characteristics that do not change over time, and δ_t denotes time-fixed effects, controlling for the impact of year-level characteristics on a firm's green transformation.

4 Empirical analysis

4.1 Benchmark regression results

Table 3 shows the results of the baseline regression on the impact of banks' digitalization on firms' green transformation. From columns (1)–columns (4) of Table 3, which are fixed effects controlling only for individuals and time, it can be seen that the regression coefficients of bank's overall digitalization, strategic digitalization, and business digitalization on enterprise green transformation are all significantly positive at the 1% level, and the regression coefficients of bank's management digitalization on enterprise green transformation are significantly positive at the 5% level. It indicates that banks' digital transformation promotes the greening of enterprises, and H1 of this paper holds. This effect

TABLE 1 Definitions of main variables.

Variable name	Variable symbols	Variable definitions
Green Transformation	GTS	Green transformation keywords word frequency plus 1 after taking the logarithm
Green Strategy	Strategy	Green strategy keywords word frequency plus 1 and then take the logarithm
Green Action	Action	Green action keywords word frequency plus 1 after taking the logarithm
Strategic Concept	Idea	Strategic concept keyword frequency plus 1 after taking the logarithm
Evaluation Planning	Plan	Evaluation planning keywords word frequency plus 1 and take the logarithm
Environmental Technology	Tech	Environmental technology keywords word frequency plus 1 and take logarithm
Pollution Control	Treat	Pollution control keyword frequency plus 1 after taking the logarithm
Monitoring Prevention	Prevent	Monitor the prevention keyword word frequency plus 1 and take the logarithm
Number of Green Patent Applications	TGreen	Add 1 to the number of green patent applications and take the logarithm
Strategic Digital Index	SDI	Strategic dimensions of digital transformation of banks
Business Digitization Index	BDI	Business dimensions of digital transformation of banks
Management Digital Index	MDI	Management dimensions of digital transformation in banks
Total Digitalization Index	TDI	Degree of digital transformation of banks
Total Return on Assets	ROA	Corporate net profit/average total assets
Financial leverage	Lev	Total liabilities/total assets
Two powers in one	Dev	President and manager are the same as 1, otherwise 0
Percentage of sole directors	Inde	Number of independent directors/Total number of board of directors
Enterprise size	Size	The number of employees is taken as a logarithm
Shareholding of top ten shareholders	Top10	Total number of shares held by the top ten shareholders/total share capital
Business Age	AGE	The age of business establishment is taken as logarithm
Provincial GDP growth rate	GDPg	Year-on-year GDP growth rates by province
Provincial Consumer Price Index	CPI	Consumer price index/100 by province
Financing constraints	SA	SA index
ESG performance	ESG	Assignment based on CSI ESG ratings
Government environmental regulations	ER	ER score of the prefecture level city where the enterprise is located
Media attention	LNMEDIA	Logarithmic number of corporate news stories

mainly stems from business digitalization in that banks integrate digital technology into the business level of the financial services they provide, followed by strategic digitalization that reflects the level of attention to digital technology at the overall strategic level of the bank. This result implies that the current progress of banks' digital transformation relies mainly on the application of digital technologies in financial products and services and the strategic level focus on digital technologies. As can be seen from columns (5)–columns (8) of Table 3, the conclusion remains unchanged with the inclusion of control variables. It can be seen that compared to the traditional banking model, banks have taken advantage of digital technology through digital transformation to give better support to enterprises in their green transformation and to facilitate their green transformation.

Table 4 further divides enterprise green transformation into green strategy transformation and green action transformation. Table 4 shows that the total index of bank digital transformation, strategy, and business dimensions significantly contribute to the green strategy and green action transformation of enterprises, while the digitalization of bank management significantly contributes to the green strategy transformation of enterprises, while it has no significant impact on the green action transformation of enterprises. Compared with the green strategy transformation of enterprises, it is more likely to promote enterprises to take green actions, truly practice corporate environmental and social responsibility, and realize green transformation, which validates the research of Wu and Li (2022).

4.2 Endogeneity issues

Therefore, this paper further takes the two instrumental variables of the spherical distance from the enterprise's registered

TABLE 2 Descriptive statistics of main variables.

Variable	Observations	Average value	Median	Minimum value	Maximum value	Standard deviation
GTS	2,372	5.09	5.01	0.00	13.24	2.45
Strategy	2,372	1.73	1.61	0.00	6.11	1.05
Action	2,372	3.37	3.33	0.00	9.01	1.75
Idea	2,372	1.61	1.61	0.00	5.51	0.97
Plan	2,372	0.12	0.00	0.00	1.95	0.29
Tech	2,372	0.33	0.00	0.00	2.89	0.56
Treat	2,372	2.44	2.56	0.00	4.73	1.02
Prevent	2,372	0.59	0.00	0.00	3.64	0.80
TGreen	2,372	79.54	0.00	0.00	1200.00	166.37
SDI	2,372	22.22	16.74	0.00	107.94	18.96
BDI	2,372	18.95	14.41	0.00	81.01	15.69
MDI	2,372	843.94	397.16	0.00	6300.00	1100.00
TDI	2,372	13.17	9.94	0.00	61.05	11.03
ROA	2,372	3.76	3.03	−64.38	47.70	5.21
Lev	2,372	50.83	51.72	4.50	98.67	17.31
Dev	2,372	0.13	0.00	0.00	1.00	0.34
Inde	2,372	36.84	33.33	23.08	66.67	5.22
Size	2,372	8.57	8.47	4.84	13.22	1.26
Top10	2,372	58.38	57.74	12.72	98.59	16.10
AGE	2,372	2.85	2.89	0.00	3.66	0.36
GDPg	2,372	10.88	9.91	−34.28	546.72	16.41
CPI	2,372	1.02	1.02	1.00	1.06	0.01
SA	2,372	−3.77	−3.80	−4.56	−2.12	0.30
ESG	2,372	6.85	7.00	0.00	9.00	1.19
ER	2,372	0.35	0.34	0.00	1.24	0.15
LNMEDIA	2,372	3.67	4.16	0.00	6.38	0.92

place to HCM City and the number of subscribers with Internet broadband access per year in each province to mitigate the endogeneity problem.

First, the spherical distance (Dis) from the enterprise's registration place to Hangzhou City is selected as an instrumental variable. In recent years, Hangzhou has become the most rapidly developing area of fintech in China, and the level of development is perennially at the leading level of the country (Guo et al., 2020), which is representative of the fact that the closer the distance between the city and Hangzhou, the higher the degree of digital transformation of the bank. However, the instrumental variables we selected do not vary over time, while bank digital transformation varies over time, so the spherical distance from the firm's place of incorporation to Hangzhou interacts with the indices of bank digital transformation dimensions to form the instrumental variable IV1 with time-varying effects (Dis*TDI, Dis*SDI, Dis*BDI, Dis*MDI).

Second, the number of users with Internet broadband access per year in each province is taken as the instrumental variable IV.2 Digital development cannot be separated from the construction of Internet infrastructure, and in regions with a higher level of Internet development, the obstacles for banks to carry out digital transformation are relatively fewer, the cost is relatively lower, and the transformation process is quicker, and it does not directly affect the green transformation of the enterprise, so the number of users with Internet broadband access is in line with the instrumental variable Exogeneity requirement.

Table 5 shows the test results for instrumental variables 1 and 2, and the test results are not substantially changed from the baseline regression results in Table 3, and there is no weak instrumental variable problem. It indicates that after controlling for possible endogeneity issues, the positive impact of bank digital transformation on corporate green transformation is still significant and the findings of this paper are robust.

TABLE 3 Impact of banks' digital transformation on corporate green transformation.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	GTS	GTS	GTS	GTS	GTS	GTS	GTS	GTS
TDI	0.0125***				0.0160***			
SDI		0.0065***				0.0082***		
BDI			0.0099***				0.0127***	
MDI				0.0001**				0.0001**
Control variables	No	No	No	No	Yes	Yes	Yes	Yes
Individuals/Years	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
_cons	3.2462***	3.2444***	3.2537***	3.2941***	−2.4805	−2.2675	−2.6600	−2.1806
N	2,372	2,372	2,372	2,372	2,372	2,372	2,372	2,372
adj. R^2	0.6713	0.6710	0.6717	0.6704	0.6736	0.6732	0.6741	0.6724

"***" indicates a significance level of 1%,"**" indicates a significance level of 5%, and "*" indicates a significance level of 10%, the same as below.

TABLE 4 Impact of banks' digital transformation on different dimensions of corporate green transformation.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Strategy				Action			
TDI	0.0073***				0.0087***			
SDI		0.0038**				0.0044**		
BDI			0.0059***				0.0068***	
MDI				0.0001**				0.0000
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individuals/Years	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
_cons	2.5023	2.5997	2.4150	2.5970	−4.9828	−4.8672	−5.0751	−4.7776
N	2,372	2,372	2,372	2,372	2,372	2,372	2,372	2,372
adj. R^2	0.3896	0.3891	0.3903	0.3887	0.6252	0.6249	0.6254	0.6242

4.3 Robustness tests

4.3.1 Changing the explanatory variables

Enterprises are the important main body of pollution prevention and the construction of ecological civilization, and innovation is the first power to lead the development of green innovation to achieve sustainable development of enterprises as the core pursuit, in reducing the consumption of natural resources at the same time can also enhance the competitiveness of the green development of enterprises. Enterprises carrying out green innovation can increase the supply of high-quality products in line with ecological and environmental standards in the production process, and improve their own product quality, revenue, and influence while bringing positive externalities to the entire economy and society. Therefore, referring to the measurement of green innovation by Li et al. (2022) and Liu et al. (2022), the findings in Table 3 are robustly tested using the number of green patent applications by enterprises.

The regression results of column (1)–column (4) in Table 6 show that there is a significant positive relationship between banks' digital transformation and firms' green technological innovation and that banks' promotion of firms' green innovation is more pronounced in the business digitization dimension, which is in line with the results of the previous test.

4.3.2 Removing the impact of major public event shocks

The rapid spread of the New Crown epidemic in 2020 was classified as a major public emergency, a major and sudden public event with great urgency and uncertainty, which posed a huge challenge to the Chinese and global economy, but at the same time, it catalyzed the rapid development of the digital economy in China (Berg et al., 2022). In the face of the demand for "contactless" services, the digital transformation of banks has been pressed on the fast-forward button, resulting in an extreme impact. Therefore, this paper excludes the sample data of 2020 and 2021, and the sample interval of the robustness test is 2010–2019. The regression results of Columns (5)–Columns (8) in Table 6 show that the digital transformation of banks significantly contributes to the green

TABLE 5 Test results for instrumental variables 1 and 2.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	First	Second	First	Second	First	Second	First	Second
	TDI	GTS	SDI	GTS	BDI	GTS	MDI	GTS
IV1	0.0004***		0.0004***		0.0004***		0.0006***	
TDI		0.1122***						
SDI				0.0656***				
BDI						0.0758***		
MDI								0.0011***
N	2,372	2,372	2,372	2,372	2,372	2,372	2,372	2,372
R^2	0.669	0.404	0.662	0.413	0.675	0.390	0.684	0.439
F-value		476.24		462.57		491.13		510.83
IV2	0.0023***		0.0042***		0.0030***		0.3098***	
TDI		0.1669***						
SDI				0.0918***				
BDI						0.1292***		
MDI								0.0013***
N	2,372	2,372	2,372	2,372	2,372	2,372	2,372	2,372
R^2	0.483	0.345	0.461	0.368	0.499	0.291	0.363	0.429
F-value		220.97		201.64		234.97		134.65

TABLE 6 Robustness test results for changing explanatory variables and excluding major public event shocks.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	TGreen	TGreen	TGreen	TGreen	GTS	GTS	GTS	GTS
TDI	0.9822***				0.0268***			
SDI		0.6137***				0.0150***		
BDI			0.6279**				0.0185***	
MDI				0.0119***				0.0003***
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individuals/Years	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
_cons	−769.8758	−762.3788	−771.0852	−773.3959	−1.9060	−1.6095	−2.1553	−1.6199
N	2,372	2,372	2,372	2,372	1,982	1,982	1,982	1,982
adj. R^2	−0.0391	−0.0384	−0.0398	−0.0367	0.5611	0.5603	0.5615	0.5592

transformation of enterprises after the exclusion of the impact of the Xinguancun epidemic, which is consistent with the results of the previous test.

4.3.3 Removal of foreign banks

Foreign banks are founded by foreign sole proprietorships, which are closely linked to their headquarters and other regional operations, and are more influenced by their home countries. Moreover, the operation mode and disclosure quality of foreign banks are different from those of Chinese banks (Liu and Shen, 2022). Therefore, this paper excludes the sample of foreign banks and is based on the digital transformation of local Chinese banks.

The regression results in Table 7 show that after excluding foreign banks, the total index of banks' digital transformation and its three sub-dimensions have a significantly positive impact on corporate green transformation at the 1% level, and the test results are basically consistent with the baseline regression results in Table 3, and the test results of this paper are robust.

TABLE 7 Robustness test results excluding foreign banks.

Variables	(1)	(2)	(3)	(4)
	GTS	GTS	GTS	GTS
TDI	0.0160***			
SDI		0.0082***		
BDI			0.0127***	
MDI				0.0248***
Control variables	Yes	Yes	Yes	Yes
Individuals/Years	Yes	Yes	Yes	Yes
_cons	−2.4805	−2.2675	−2.6601	−2.4015
N	2,372	2,372	2,372	2,372
adj. R^2	0.6736	0.6732	0.6741	0.6732

5 Mechanism of action tests

5.1 Conduction mechanism test

5.1.1 Financing constraint mechanisms

The digital transformation of banks under the development of digital technology has pushed banks to make concessions to enterprises, which has brought about a breakthrough in alleviating the problem of enterprise financing (Gomber et al., 2018; Li et al., 2022), and has helped to improve the match between credit resources in terms of "quantity" and resource allocation in terms of "quality", thus realizing the role of the financial sector in promoting the green transformation of enterprises. "Quality" of credit resources and resource allocation, thereby realizing the financial sector's role in promoting the green transformation of enterprises. Currently, the mainstream measurement of financing constraints includes the SA index, KZ index and WW index, of which the SA index is more exogenous than the KZ index, and WW index, therefore, this paper refers to the research of Ju et al. (2013) to take SA index as a measure of corporate financing constraints.

Table 8 shows the test results of the transmission mechanism of financing constraints in banks' digital transformation and enterprises' green transformation. The mechanism test in this paper refers to the method of median grouping regression, which calculates the median of enterprises' financing constraint samples, and according to the median of the samples, the enterprises are divided into two groups of enterprises with low financing constraints and high financing constraints. Columns (1)–(4) show that all dimensions of bank digital transformation can significantly promote the green transformation of enterprises with low financing constraints at the 1% level, and columns (5)–(8) show that none of the dimensions of bank digital transformation effectively promotes the green transformation of enterprises with high financing constraints. This implies that as the process of bank digital transformation accelerates, in general, it will reduce the financing threshold, release the dividend of financial services, and effectively alleviate the problem of enterprise financing constraints, thus achieving the effect of promoting the green transformation of enterprises, which verifies H2. This is consistent with the findings of Guo et al. (2023), Tan et al. (2023).

5.1.2 ESG performance mechanisms

The ESG concept requires companies to develop themselves without compromising the sustainable development of the economy and society, and the ESG rating system complements formal environmental regulation by demonstrating to the external market the performance of companies in terms of environmental and social responsibility and corporate governance through professional rating agencies. Therefore, Corporate ESG performance is an important way to urge corporate green transformation. In this paper, according to the median of corporate ESG performance samples, enterprises are divided into two groups good ESG performance and poor ESG performance for mechanism testing.

Table 9 presents the results of testing the transmission mechanism of firms' ESG performance in banks' digital transformation and firms' green transformation. Columns (1)–Column (4) show that none of the bank digital transformation dimensions contribute effectively to the green transformation of firms with poor ESG performance. Columns (5)–Column (8) show the results of regressions of bank digitalization dimensions on green transformation of firms with good ESG performance. Columns (5) and (7) show that total bank digitalization index and business digitalization significantly contribute to the green transformation of ESG-performing firms at the 5% level, column (6) shows that bank strategic digitalization significantly contributes to the green transformation of ESG-performing firms at the 1% level, and column (8) shows that bank management digitalization fails to significantly contribute to the green transformation of ESG-performing firms. In general bank digitalization effectively promotes the green transformation of ESG-performing firms, validating H3. This implies that ESG ratings improve the external information environment of firms, connect firms to the market, and help ESG-performing firms to obtain more support from banks and other sources, which provides intrinsic motivation for firms' green transformation, validating the findings of Zhang (2023), Wang and Esperança (2023) studies.

Tables 8, 9, while validating the results of Feng et al. (2022) study on fintech-enabled corporate green development, also provide new ideas on how the financial industry can empower corporate green transformation in the era of digital economy.

5.2 Regulatory mechanism test

5.2.1 Government environmental regulation

Government environmental regulation is an important policy instrument to stimulate enterprises to carry out green transformation, and when the intensity of government environmental regulation is high in a certain region, it will increase the cost of heavily polluting enterprises and stimulate enterprises to carry out green transformation. To examine the moderating effect of environmental regulation on the relationship between bank digitization and enterprises' green transformation,

TABLE 8 Transmission mechanism test: Financing constraint channels.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	GTS	GTS	GTS	GTS	GTS	GTS	GTS	GTS
	Low financing constraints				High financing constraints			
TDI	0.0318***				0.0066			
SDI		0.0179***				0.0026		
BDI			0.0225***				0.0066	
MDI				0.0003***				−0.0000
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individuals/Years	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
_cons	−0.4134	−0.3749	−0.4037	−0.4201	0.7972	0.8008	0.8615	0.6096
N	1,165	1,165	1,165	1,165	1,207	1,207	1,207	1,207
adj. R^2	0.5607	0.5601	0.5612	0.5593	0.6217	0.6215	0.6221	0.6214

TABLE 9 Conduction mechanism test: ESG performance.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	GTS	GTS	GTS	GTS	GTS	GTS	GTS	GTS
	ESG performance poor				ESG performs well			
TDI	0.0080				0.0135**			
SDI		0.0034				0.0068*		
BDI			0.0074				0.0110**	
MDI				0.0000				0.0001
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individuals/Years	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
_cons	1.9326	1.8472	2.0223	1.4417	−2.9745	−2.6657	−3.2386	−1.9911
N	1,073	1,073	1,073	1,073	1,299	1,299	1,299	1,299
adj. R^2	0.5595	0.5592	0.5599	0.5589	0.6704	0.6701	0.6707	0.6694

this paper introduces the intensity of government environmental regulation (ER) that enterprises are subject to and its interaction term with the dimensions of bank digitization to construct a moderating effect test model, and to ensure the robustness of the results, the explanatory variables (TDI, SDI, BDI, MDI) and the moderating variables of government environmental regulation (ER) are decentralized by processing, and then construct the interaction terms.

The results in Table 10 show that the interaction terms of environmental regulation with total bank digitization index (ERTDI_C), with bank strategy digitization (ERSDI_C), and with bank business digitization (ERBDI_C) are all significantly positive, while the interaction term of government environmental regulation with bank management digitization (ERMDI_C) is not significantly positive, but in general it can show that the government environmental regulation has a positive moderating effect on the relationship between bank digitization and corporate green transformation. Regulation has a positive moderating effect on the relationship between bank digitization and corporate green transformation, which validates H4. The reason is that government environmental regulation is an important institutional tool formulated by the government to protect the environment, and serves to constrain corporate pollutant emissions and other behaviors that are detrimental to environmental protection (Cai et al., 2020; Cao et al., 2021). Government environmental regulations regulate and supervise the rational use of bank loans by enterprises, penalize enterprises that pollute more and are unwilling to change their original production methods, increase the costs of the enterprises concerned, and motivate

TABLE 10 Moderating effect test: Government environmental regulation.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	GTS	GTS	GTS	GTS	GTS	GTS	GTS	GTS
ER	−0.0663	−0.0471	−0.0637	−0.0428	−0.0698	−0.0512	−0.0645	−0.0448
TDI	0.0160***	0.0176***						
ERTDI_C		0.0310*						
SDI			0.0082***	0.0094***				
ERSDI_C				0.0192**				
BDI					0.0127***	0.0136***		
ERBDI_C						0.0199*		
MDI							0.0001**	0.0001**
ERMDI_C								0.0002
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individuals/Years	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
_cons	−2.3416	−2.5177	−2.1338	−2.4687	−2.5143	−2.5580	−2.0454	−2.4564
N	2,372	2,372	2,372	2,372	2,372	2,372	2,372	2,372
adj. R^2	0.6735	0.6739	0.6731	0.6736	0.6740	0.6744	0.6723	0.6725

enterprises to raise their awareness of environmental management and carry out green transformation.

5.2.2 Media attention

With the intensification of environmental and sustainable development issues, the media's attention to corporate environmental issues has increased, and given the media's role as a watchdog and information intermediary, it has an important impact on corporate green transformation. To examine the moderating effect of media attention on the relationship between bank digitization and corporate green transformation, this paper introduces the media attention received by corporations (LNMEDIA) and its interaction term with the dimensions of bank digitization to form a moderating effect test model, and to ensure the robustness of the results, the explanatory variables (TDI, SDI, BDI, MDI) and the moderating variable media attention (LNMEDIA) are pair-centered and then the interaction terms are constructed.

The results in Table 11 show that the interaction terms between media attention and each dimension of bank digitization are all significantly positive at the 1% level, indicating that media attention has a positive moderating effect on the relationship between bank digitization and corporate green transformation, validating H5. The reason is that media attention is an important complement to government regulation, and media coverage can improve corporate information transparency, increase public attention to corporate green transformation, and increase the likelihood of government regulatory intervention, increasing the difficulty and cost of polluting production activities by firms, thus regulating their environmental behavior (Wang F. et al., 2022; Jie and Jiahui, 2023). Enterprises accelerate their green transformation to protect their reputation and obtain bank credit support.

6 Heterogeneity test

6.1 Degree of digitization of firms

A certain degree of enterprise digitization is a prerequisite for banks to capture the "digital footprint" of enterprises, effectively alleviate the information asymmetry between banks and enterprises, and then promote the green transformation of enterprises. Therefore, based on the CSMAR database data on the degree of digital transformation of enterprises, this paper divides enterprises into two groups with low and high degrees of digitalization according to the median degree of digital transformation of enterprises and examines whether the different degrees of digital transformation of enterprises cause the heterogeneous impact of bank digitalization on green transformation of enterprises.

The results of columns (1)–column (4) of Table 12 show that in the case of low enterprise digitization, the total digitization index and business digitization of banks promote enterprise green transformation at the level of 10 percent and 5 percent, respectively, whereas strategic digitization and managerial digitization of banks fail to contribute significantly to the green transformation of enterprises. The results in columns (5)–(8) show that in the case of high enterprise digitization, banks' total digitization index, strategic digitization, and business digitization all contribute significantly to the green transformation of enterprises, and the coefficients are larger than those in the group with low enterprise digitization, indicating that banks'

TABLE 11 Moderating effect test: Media attention.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	GTS	GTS	GTS	GTS	GTS	GTS	GTS	GTS
LNMEDIA	−0.0423	−0.0433	−0.0414	−0.0427	−0.0429	−0.0434	−0.0399	−0.0415
TDI	0.0162***	0.0187***						
LNMEDIATDI_C		0.0043*						
SDI			0.0083***	0.0099***				
LNMEDIASDI_C				0.0025*				
BDI					0.0128***	0.0142***		
LNMEDIABDI_C						0.0029*		
MDI							0.0001**	0.0001**
LNMEDIAMDI_C								0.0000
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individuals/Years	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
_cons	−2.2537	−2.7332	−2.0433	−2.5275	−2.4309	−2.8924	−1.9650	−2.2962
	(0.7155)	(0.6585)	(0.7411)	(0.6829)	(0.6940)	(0.6398)	(0.7511)	(0.7112)
N	2,372	2,372	2,372	2,372	2,372	2,372	2,372	2,372
adj. R2	0.6737	0.6741	0.6733	0.6736	0.6742	0.6745	0.6724	0.6725

TABLE 12 Heterogeneity test based on the degree of digitization of firms.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	GTS	GTS	GTS	GTS	GTS	GTS	GTS	GTS
	Low level of enterprise digitization				High level of enterprise digitization			
TDI	0.0124*				0.0129**			
SDI		0.0057				0.0067*		
BDI			0.0101**				0.0108**	
MDI				0.0001				0.0001
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individuals/Years	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
_cons	−21.0193**	−20.8794**	−21.1808**	−20.8150**	20.1967**	20.3351**	20.1179**	20.4461**
N	1,167	1,167	1,167	1,167	1,205	1,205	1,205	1,205
adj. R^2	0.5579	0.5574	0.5584	0.5569	0.7010	0.7008	0.7014	0.7000

digitization is more capable of facilitating the green transformation of enterprises with high digitization.

6.2 Nature of property rights

Traditional finance is more inclined to allocate funds to state-owned enterprises, which creates an attribute mismatch problem and slows down the process of the financial system supporting the high-quality development of enterprises. In the previous paper, it has been verified that the digital transformation of banks can promote the green transformation of enterprises, but whether it can correct the mismatch problem and improve the ability of finance to support the green development of enterprises still needs to be further explored. Therefore, this paper divides enterprises into state-owned and non-state-owned parts according to the nature of their property rights.

The regression results in columns (1)–(4) of Table 13 show that all dimensions of bank digitization significantly contribute to corporate green transformation at the 1% level. The regression

TABLE 13 Heterogeneity test based on the nature of property rights.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	GTS	GTS	GTS	GTS	GTS	GTS	GTS	GTS
	Non-state-owned				State-owned			
TDI	0.0256***				0.0112**			
SDI		0.0133***				0.0056*		
BDI			0.0197***				0.0093**	
MDI				0.0002***				0.0000
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individuals/Years	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
_cons	−18.0371	−18.2352	−17.6737	−18.7494	2.6854	2.9015	2.4472	3.2966
N	782	782	782	782	1,590	1,590	1,590	1,590
adj. R^2	0.6683	0.6674	0.6691	0.6671	0.6676	0.6673	0.6679	0.6668

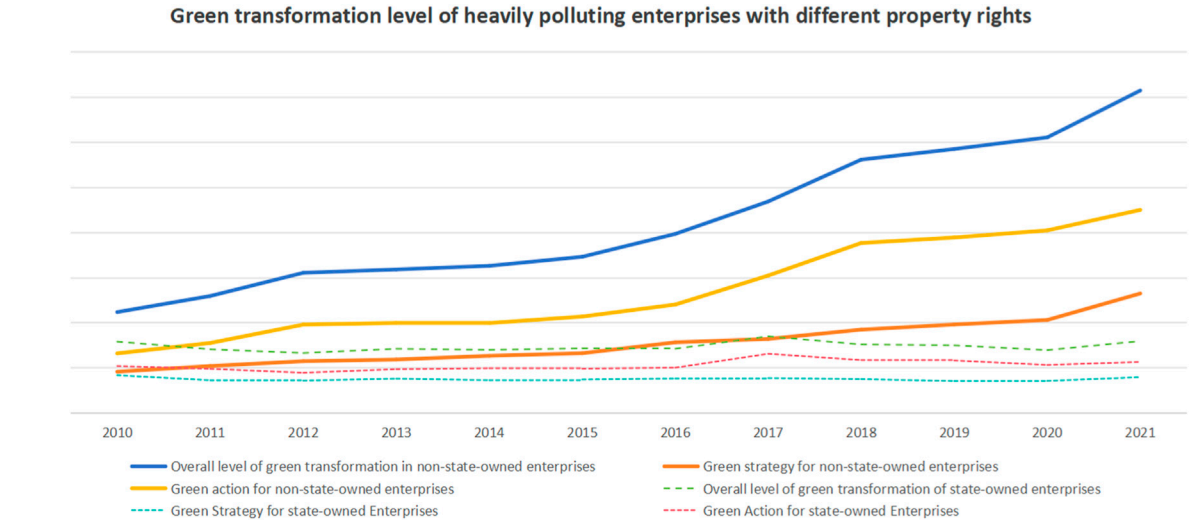


FIGURE 1
Green transformation level of heavily polluting enterprises with different property rights.

results in columns (5)–(8) show that for SOEs, the total bank digitization index, business digitization significantly contributes to corporate green transformation only at the 5% level, while bank strategic digitization contributes to corporate green transformation only at the 10% level. The overall results suggest that non-state-owned enterprises better reflect the green-driven effect of bank digitization. This suggests that compared to the traditional financial model, the policy and capital advantages of SOEs are weakened to a certain extent with the digital transformation of banks, making the attribute mismatch problem less severe.

Figure 1 shows the level of green transformation of heavily polluting enterprises with different property rights. From Figure 1, we can also see that the level of green transformation of non-state-owned heavy-polluting enterprises is much higher than that of state-owned enterprises and shows a stable upward trend. The regression results in Table 13 are supported by the fact that state-owned enterprises themselves have abundant funds, implicit guarantees, weak awareness of change, and low sensitivity to transformation. Non-state-owned enterprises, to improve their competitiveness, need to timely capture future development directions, discover market green development signals, and carry out green transformation.

6.3 Regional division

Under the promotion of a series of policy initiatives in China, the overall economic development of China has been greatly improved,

TABLE 14 Heterogeneity test based on region.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	GTS	GTS	GTS	GTS	GTS	GTS	GTS	GTS
	Eastern part				The central and western part			
TDI	0.0176***				0.0134**			
SDI		0.0089**				0.0069*		
BDI			0.0143***				0.0105**	
MDI				0.0001				0.0001
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individuals/Years	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
_cons	−0.1966	−0.0595	−0.3349	−0.0846	−1.5437	−1.3764	−1.6430	−1.3905
N	1,357	1,357	1,357	1,357	1,015	1,015	1,015	1,015
adj. R^2	0.6767	0.6763	0.6774	0.6752	0.6663	0.6660	0.6667	0.6657

but there are still problems of inadequacy and incoherence. Compared with the eastern region, the central and western regions are limited by factors such as regional mismatch of production factors and low efficiency of digital technology absorption, resulting in a low level of regional development of the digital economy, and the aggregation of financial resources to economically developed regions, which limits the development of enterprises in less developed regions.

Therefore, this paper divides enterprises by region into two parts, the eastern coastal region, and the central and western inland region, according to where they belong to for the heterogeneity test. The regression results in Table 14 show that in general, the facilitating effect of bank digitization on the green transformation of enterprises in the eastern region is higher than that in the central and western regions both in terms of significance and coefficients, which validates the study of Li et al. (2022). It indicates that although the development of the digital economy also provides convenient digital financial services for the central and western regions, the development of bank digitalization in the central and western regions is still slower than that in the eastern region, and the facilitating effect on the green transformation of enterprises is smaller than that in the eastern region. However, it also shows that there is relatively more room for banks' digital transformation in the western region, and government departments should increase the construction of digital infrastructure in the central and western regions to provide a reference for how banks' digitalization can help the high-quality development of the regional economy.

7 Further analysis

In order to further explore the sub-dimensional impact of bank digitization on corporate green transformation, this paper further subdivided green strategic transformation into two dimensions: strategic concept and assessment planning, and green actions into three dimensions: environmental technology, emission control, and monitoring and prevention.

TABLE 15 Further analysis.

Variables	Green strategy		Green action		
	(1)	(2)	(3)	(4)	(5)
	Idea	Plan	Tech	Treat	Prevent
TDI	0.0066***	0.0007	0.0025	0.0009	0.0053***
SDI	0.0034***	0.0003	0.0012	0.0003	0.0029***
BDI	0.0053***	0.0006	0.0020*	0.0009	0.0039***
MDI	0.0001**	0.0000	0.0000	−0.0000	0.0000**
Control variables	Yes	Yes	Yes	Yes	Yes
Individuals/Years	Yes	Yes	Yes	Yes	Yes
N	2,372	2,372	2,372	2,372	2,372

Table 15 shows the regression results based on each sub-dimension of corporate green transformation5. The results in column (1) show that all dimensions of bank digitization significantly increase the importance of green transformation by corporate management and promote the establishment of green strategic concepts by corporations. The results in column (2) show that none of the bank digitization dimensions significantly contribute to the implementation of assessment planning for green transformation in enterprises. Column (3) results show that banking digitization significantly promotes firms' environmental technology upgrading at a 10% level. Column (4) results show that all dimensions of banking digitization significantly promote firms to undertake emissions management. The results in column (5) show that all dimensions of banking digitalization significantly promote firms for monitoring and prevention at a 1% level. The results of further

analyses validate the findings of Li and Wang (2021), and Duan et al. (2023) that there is a discrepancy between what enterprises say and what they do in the process of green transformation. It shows that the digital transformation of the bank is more to enhance the importance of enterprise management on green and promote enterprises to monitor and prevent environmental aspects, but the enterprises have not yet formed a systematic and effective green transformation planning. At the same time, heavily polluting enterprises have limited financial resources and lack the funds to carry out high-cost equipment renewal, process modification, and sewage treatment.

8 Conclusion, policy recommendations, and outlook

8.1 Conclusion

Based on the annual data of Chinese A-share heavily polluting listed companies from 2010 to 2021, this paper empirically analyses whether the digital transformation of banks affects the green transformation of enterprises and its possible internal mechanisms, and the findings are as follows:

Digital transformation of banks facilitates the green transformation of firms. This finding remains robust after eliminating endogeneity issues and a series of robustness tests. It is also found that the strategic digitalization and operational digitalization dimensions of banks have a more pronounced effect on driving corporate green transformation than their managerial digitalization, and are mainly reflected in the transformation of corporate green actions.

Bank digital transformation facilitates corporate green transformation through two channels: mitigating corporate finance constraints and improving corporate ESG performance, both of which are effective on the bank strategy and business digitalization sub-dimensions, while only the mitigating finance constraints channel is effective on the bank management digitalization dimension.

The facilitating effect of bank digital transformation on firms' green transformation is heterogeneous. Banks' digital transformation has a facilitating effect on enterprises with different degrees of digitization, but the green-driving effect is more obvious for enterprises with a high degree of digitization. The facilitating effect of bank digital transformation on the green transformation of non-state-owned enterprises is higher than that of state-owned enterprises, indicating that bank digital transformation corrects the attribute mismatch problem to a certain extent. The facilitating effect of bank digital transformation on the green transformation of enterprises in the eastern coastal region is greater than that in the inland central and western regions, suggesting that the digital transformation of banks in the central and western regions needs to be accelerated.

8.2 Policy recommendations

Based on the above findings, this paper makes the following policy recommendations:

Commercial banks should take the initiative to embrace digitalization and accelerate the promotion of digital transformation and upgrading. The construction of Digital China has become an important engine for promoting Chinese-style modernization in the digital era, and the banking industry, as an important force for promoting economic and social progress, is bound to accelerate the promotion of digital transformation. Therefore, banks should increase investment in financial technology, attract scientific and technological talents, and promote the intelligence of each service link. Through digital means to empower the green transformation of enterprises and improve the allocation efficiency of credit resources.

Enterprises should strengthen ESG concepts, enhance ESG practices, and focus on the implementation of green actions. In the past, China's ESG information disclosure requirements for enterprises were low, with voluntary disclosure as the main focus, resulting in many enterprises coping with ESG information disclosure, more abbreviated descriptions of corporate ESG information, poor reliability, and overall low quality of information, which is not conducive to the use of digital technology by banks to capture the ESG performance of the enterprise, and may lead to difficulties in obtaining corporate credit. This requires enterprises to strengthen their own ESG information disclosure, which also coincides with the current construction of China's ESG information disclosure. At the same time, enterprises should also put green transformation into action, enhance their competitiveness in green development, and contribute to the high-quality development of the economy.

The Ministry of Ecology and Environment and other departments should promote the construction of an ESG evaluation system with Chinese characteristics, and promote data sharing of ESG information between commercial banks and enterprises. Although the Ministry of Ecology and Environment has set up a special agency for ESG, and the State-owned Assets Supervision and Administration Commission (SASAC) is constantly regulating the disclosure of ESG information of listed companies held by central enterprises, China's ESG information system is completely adapted from foreign frameworks without fully taking into account China's national conditions. Relevant departments in China should grasp the relationship between domestic and international standards, refer to ISSB's global ESG reporting standards, and construct a scientific and standardized ESG indicator system with Chinese characteristics. The results of this paper found that the digital transformation of banks can promote the green transformation of enterprises by improving their ESG performance. In practice, banks are unable to obtain timely and accurate corporate ESG information before lending, which causes delays in credit approval. Ecological and environmental departments should strengthen coordination with banks and take the lead in realizing the sharing of information resources among commercial banks, enterprises, and ecological and environmental departments.

The government should improve the construction of infrastructure related to digital technology to create favorable conditions for the digital transformation of banks. Weak digital infrastructure will hinder the process of banks' digital transformation. Therefore, the government should consider increasing funding to improve the construction of digital

infrastructure such as broadband networks, and subsidizing the introduction of talent to strengthen the robustness of digital infrastructure. In particular, it should accelerate the improvement of digital infrastructure in the central and western regions to create conditions for them to catch up with the digital transformation of banks in other regions.

8.3 Outlook

In exploring the impact of bank digitalization on corporate green transformation based on the sub-dimensions of corporate green transformation, this paper finds that there is an symmetry in this impact. Overall bank digitalization promotes corporate green transformation, with differences in corporate green transformation under the sub-dimensions. Bank digitalization significantly promotes enterprises' green transformation in terms of strategic concepts and monitoring and prevention, but not in terms of enterprises' green assessment planning, environmental technology upgrading and upgrading, and sewage treatment, and the specific reasons for this problem need to be further explored.

It should be noted that the study in this paper has some limitations. First, the study in this paper only focuses on Chinese heavy polluters, and future studies should include global samples, and other types of enterprises in China to guarantee the applicability of the results. Second, bank digitalization is an all-around and systematic change, and with the development of digital technology, the index of bank digital transformation needs to be refined. Finally, there are still unexplored avenues between bank digitalization and the green transformation of heavily polluting enterprises. There are rich avenues for bank digitization to influence the green transformation of firms, and the role of enterprise risk between bank digitization and the green transformation of firms can be further explored in the future.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

KJ: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing–review and editing. YuZ: Data curation, Formal Analysis, Investigation, Methodology, Software, Visualization, Writing–original draft. YaH: Supervision, Formal Analysis, , Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Will the miniaturization of household size promote household carbon emissions in China? Analysis based on CFPS data

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As the proportion of household carbon emissions to global carbon emissions continues to increase, reducing carbon emissions from household consumption has become an important way to achieve the goals of carbon peaking and carbon neutrality. How the trend of miniaturization of household size will affect household carbon emissions is a matter of concern. This paper uses a sample of 9,090 households from the China Family Panel Studies (CFPS) database in 2018 to empirically study the impact of changes in household size on household carbon emissions, from the perspective of household consumption structure and urban-rural areas. The research results indicate that the miniaturization of household size will increase household carbon emissions, the impact of household size on indirect HCEs is greater than on direct HCEs. The impact of household size on indirect HCEs is heterogeneous in consumption structure and the impact of household size on indirect HCEs from housing, transportation is greater than that of other consumption items. The impact of household size on urban household carbon emissions is greater than that in rural areas. The upgrading of household consumption structure and the miniaturization of household size promote the increase of HCEs jointly. Therefore, this paper proposes that under the trend of household miniaturization, energy-saving and emission reduction policies should focus on reducing indirect households carbon emissions, optimizing household structure and household consumption structure, enhancing environmental awareness among family members, establishing and improving the green consumption system, and building environment-friendly households.

KEYWORDS

household carbon emissions, household size, household consumption structure, the CFPS data, indirect household carbon emissions

1 Introduction

Global warming and environmental pollution have become severe issues facing humanity. Scientists have identified the primary cause of global climate warming as greenhouse gas emissions, with carbon dioxide being the major component (Hardee and Mutunga, 2010). Reducing carbon emissions is essential to address this problem.

Many countries have taken actions to mitigate carbon emissions and committed to achieving carbon neutrality. Traditionally, government-implemented carbon reduction measures have primarily targeted the supply-side sectors, such as the industrial sector, which consumes a significant portion of energy. However, with economic and social development, increasing research indicates that a substantial proportion of carbon emissions is attributed to household consumption. Therefore, demand-side measures should receive more attention in mitigating climate change (Liu et al., 2003). In particular, the household sector plays a crucial role in carbon reduction (Nejat et al., 2015; Ivanova et al., 2016; Klemes et al., 2021; Goldstein, 2022). The household size miniaturization has become a global demographic development, profoundly affecting production and lifestyles, which in turn impacts the environment (Liu et al., 2003; Wang, 2015).

Research on household carbon emissions originates from the relationship between demographic factors and energy consumption and carbon emissions (Jiang L W, 2011). Studies on demographic factors and carbon emissions are primarily based on the IPAT formula (Paul Ehrlich and John Holdren, 1971) and the stochastic form of the STIRPT model (York et al., 2003), expanding population factors from population size (Shi, 2003; Baige, 2010; Peng Xizhe, 2010) to include demographic structure factors (Jiang, 2010), such as population aging (Nan et al., 2011) and urbanization (Satterthwaite, 2009). Some scholars have also focused on household-level impacts (Dalton et al., 2008). However, these studies analyze the impact of household changes on carbon emissions from a macro perspective, failing to delve into how changes in household characteristics affect the environment. Households, as units of population analysis influencing carbon dioxide emissions, may be more effective than individuals, especially in developing countries (Jiang, 2010). From the household perspective, carbon emissions can be measured through household consumption behavior. Household carbon emissions are mainly influenced by household structural characteristics and consumption behavior (Bin and Dowlabdi, 2005). Household carbon emissions result from consumption behavior, and household characteristics and socioeconomic traits influence consumption patterns, which in turn affect household carbon emissions (Büchs M, 2013; Xu et al., 2016). Key household characteristics include household income (Weber and Matthew, 2008; Suling Feng et al., 2023), household size (Ivanova, Büchs, 2020), household head's educational level (Janaki Imbulana Arachchi, 2022; Zhang, 2023), energy structure (Nair et al., 2019), and geographic location (Yu et al., 2023).

Household size is a significant demographic characteristic and an important factor affecting household carbon emissions. The impact of household size on carbon emissions primarily stems from household economies of scale (Ellsworth-Krebs, K., 2020; Shiwang et al., 2023). Economies of scale in households mean that members share household space, basic facilities (appliances, tools, and equipment), and other consumer goods (Ivanova, Büchs, 2020). As household size increases, *per capita* living costs decrease while maintaining the same living standard (Deaton A S, 1998). Therefore, as household size decreases, the economies of scale at the household level diminish, potentially increasing *per capita* energy consumption (Jiang, 2010; Wang, 2015; Milena Büchs, 2022; Zhang, 2023).

Different consumer goods have different economies of scale, depending on the composition of household members (Thaiyoong, 2011). Current research on these issues mainly explores income and consumption levels (Wang, 2015), neglecting the impact of changes in consumption structures. Some studies have noted the influence of consumption structures on carbon emissions (Wei et al., 2007; Weber and Matthews, 2008; Xu and Han, 2017), but they do not analyze household characteristics. Some scholars analyze the impact of household size on direct and indirect carbon emissions, suggesting that the negative impact of household size on indirect carbon emissions is greater than on direct carbon emissions (Zhang, 2022; Cong et al., 2023; Meng, 2023). Hongwu Zhang et al. (2020) argues that over time, the lifestyles of different social strata are becoming increasingly carbon-intensive, recommending that climate change research and policy-making consider the growing impact of lifestyles. Han et al. (2023) points out that with increasing household incomes, consumption structures change, with a lower proportion spent on food and higher proportions on transportation, communication, and housing, leading to higher household carbon emissions. The impact of household size on carbon emissions from food, transportation, communication, and housing consumption warrants further discussion.

China is a major emitter of carbon and has a large population. Despite leading the global clean energy economy, China's carbon dioxide emissions and *per capita* emissions continue to grow, with an increase of approximately 565 million tons in 2023, making China's *per capita* emissions 15% higher than those of developed economies (IEA, 2023). In 2020, to address global climate challenges, the Chinese government committed to achieving peak carbon emissions by 2030 and carbon neutrality by 2060. With rapid income growth, household consumption in China has become the second-largest energy-consuming sector after the industrial sector (Qu Jiansheng, 2014). Over 70% of household consumption expenditure occurs within the household sector (Liu et al., 2011), making household consumption a significant source of carbon emissions in China (Sun, 2022). In 2022, China's population showed negative growth, while the aging of the population continued to deepen. China's population aged 60 and over was 280 million, accounting for 19.8% of the national population, of which 210 million were aged 65 and over, accounting for 14.9% of the national population (China's National Bureau of statistics, 2023). The accelerating process of population aging has led to the increasing number of empty nest families. Receiving higher education and the pressure of working and living lead to more young people marrying and having children late. The postponement of the first marriage age and the increase of the interval between first marriage and first childbirth have increased the proportion of single person households and two person households. The aging of the population and the expansion of population mobility have increased the proportion of empty nest families and families living alone. Low birth rate, population aging, urbanization, rising divorce rate and other factors jointly promote the continuous shrinking of household size in China (Wang and zhou, 2021). According to the seventh national census, the average household size in China decreased from 5.3 members in the 1950s to 3.1 in 2010 and 2.62 in 2020. The number of households has steadily increased, reaching 494,157,423 in 2020, an increase of 92.64 million from 2010. Over 125 million households are single-person households,

accounting for 25.4% of total households, while two-person households account for 29.7%, and three-person households account for 21% (National Bureau of Statistics, 2021). The significant shrinking in household size and changes in household consumption patterns in China raise questions about their impact on household carbon emissions, an important issue for achieving carbon reduction and carbon neutrality goals.

Yu et al. (2023) used data of Jiangsu Province from 2015–2019 to find a negative correlation between household size and *per capita* HCEs in China. Yimeng Zhang and Zhang (2023) analyzed urban household data from 1992–2012 to examine the impact of household structural changes on carbon emissions. The former uses provincial data, while the latter only uses micro data of urban households. These recent studies on China focus on the relationship between household size and *per capita* household carbon emissions, analyzing the differences between direct and indirect carbon emissions but not from the perspective of consumption structure. The novelty and contribution of this study is as follows: (1) this study uses the GFPS data in 2018. The GFPS database covers the whole country, including urban families and rural families, which is more representative. (2)With economic development and rising income levels, household consumption patterns in China have shifted from survival-based to development-based and enjoyment-based, potentially increasing household carbon emissions (Zhang, 2020; Han et al., 2023). This study explores the impact of household size on household carbon emissions from the perspective of household consumption structure, comparing differences in eight categories of household consumption expenditure: food, clothing, housing, household goods and services, transportation and communication, education, culture and entertainment, healthcare, and other goods and services. The study examines whether smaller households exhibit high carbon emission consumption patterns. (3)Additionally, considering the inequality in development between urban and rural areas in developing countries, the study analyzes the disparity in household carbon emissions between urban and rural households, exploring whether the miniaturization of household size and urbanization in China exacerbates this inequality. This study comprehensively analyzes the impact of household size on household carbon emissions, as well as the heterogeneity of urban and rural areas and consumption structure, which helps to formulate more targeted and differentiated household carbon emission reduction strategies.

2 Research review

Household carbon emissions (HCEs) have been widely discussed. Existing studies mainly focused on the quantitative assessment of household carbon emissions, sources, and analysis of key influencing factors.

2.1 Measurement of household carbon emission

The measurement of household carbon emission is the basis of this study. and the HCEs refer to CO2 emissions caused by residents' living consumption (Mi et al., 2020) and transportation (Fan et al., 2022) in household life. HCEs can be divided into direct and indirect HCEs (Bin and Dowlatabadi, 2005; Wei et al., 2007; Wang et al., 2019). Estimation of HCEs is generally carried out by this classification (Sun Y, 2022). Direct HCEs refer to direct household energy consumption, such as coal, natural gas, and other resources consumed by lighting, electrical appliances, cooking, and private transportation activities (Santill' an et al., 2021). Indirect HCEs refer to CO2 generated in the production process of electricity, food, clothing and daily necessities, household equipment, transportation, and entertainment services (Liu et al., 2019).

The input-output method (IOM), consumer lifestyle approach (CLA), IPCC inventory method (IPC-RA) and life cycle assessment (LCA) are the main methods to measure HCEs (Zhang et al., 2015). Input-output method mainly evaluates indirect carbon emissions from macro-statistical data or micro-survey data of various countries and regions (Hereundeen and Tanaka, 1976; Weber and Perrels, 2000; Zhang Q.J. et al., 2019). But there is a lag in calculating carbon emissions by this method, which can lead to situations where the emissions accounting is impossible because of the incomplete input-output tables for some years (Wang et al., 2019). The consumer lifestyle approach typically calculates indirect carbon emissions from household consumption by multiplying household consumption expenditure by the IOM emission coefficients (Bin and Dowlatabadi, 2005; Fan and Wang, 2014; Xu X et al., 2016; Hu Z. et al., 2020). For IPCC inventory method, it uses macro statistics or micro-survey data from various countries, regions, and provinces and cities to directly assess carbon emissions (Ma X.W. et al., 2015; Li N. N. et al., 2022). This method is a commonly used approach by most scholars for measuring direct household carbon emissions. However, there is a significant difference in the carbon emission coefficients for the same energy source due to the inconsistency in energy production levels across different regions, leading to a certain deviation from the actual situation (Liu et al., 2013). The life cycle assessment calculate the greenhouse gas emissions generated throughout the entire lifecycle of products and services (Nissinen et al., 2006). LCA provides precise measurement results, but its requirement for more accurate data also makes it challenging to measure carbon emissions on a large scale (Li et al., 2015; Miehe et al., 2016).

2.2 The key influencing factors of household carbon emissions

Existing research on the factors influencing HCEs primarily focuses on two aspects: household demographic characteristics and consumption patterns. Different household characteristics lead to varied household consumption decisions, thereby affecting the household carbon footprint (Bin and Dowlatabadi, 2005). Household characteristics that significantly influence HCEs include household size, income, household member composition, gender of the head of household, education level, and the location of the family's housing. Consumption factors affecting household carbon emissions are mainly derived from family income, savings, and consumption patterns. There are also studies that analyze the impact from the perspective of the family's material

foundation and lifestyle, such as housing and transportation (Xue Y.Z.,2020; Meng X.Z.,2023; Dusan Gordic, 2023). In general, scholars investigate the factors of HCEs based on specific attributes of the family (Xiang H.L., 2022).

2.2.1 Household income

Household income is a prominent factor affecting household carbon emissions (Wang 2015; Wang et al., 2018; Cao et al., 2019). The IPCC report in 2022 revealed that households in the top 10% of income contribute 36%–45% of global GHG emissions (IPCC et al., 2022). Household income levels influence consumption levels, and there is a positive correlation between income levels and household carbon emissions. Sumita Nair et al. (2019) conducted a study focusing on energy, transportation, and petroleum and natural gas consumption related to direct carbon emission activities and concluded that there is a positive correlation between household income and direct carbon emissions. Weber and Matthews (2008) found that carbon emissions are mainly concentrated in consumption for basic needs for low-income families, and as income levels rise, the proportion of carbon emissions associated with higher-level consumption categories, such as entertainment, also increases. Affluent families have greater consumption power and higher demand for goods and services, leading to more indirect carbon emissions (Zheng et al., 2020; Hartono, 2023). The household carbon footprint is also related to family wealth (Zhao et al., 2023; Su L.F., et al., 2023). Possessing a house enhances a family's wealth, which in turn raising the consumption level and consequently increasing household carbon emissions (Ying et al., 2023). In addition, some studies also suggest a negative correlation between the highest income levels and HCEs (Sharma et al., 2021). Although researchers' conclusions may vary, they all reveal the significant impact of household income on HCEs. Therefore, incorporating household income into this study will help to understand the combined carbon emission effects of household size and income, and assist governments in formulating more accurate carbon reduction policies.

2.2.2 Education level

It is generally believed that education level shows a negative correlation with both household energy use and carbon emissions (Golley et al., 2008; Brand et al., 2013). Education has a positive impact on HCEs (Yi et al., 2007; Büchs and Schnepf, 2013). Individuals with higher levels of education may be more eager to achieve a higher quality of life and prefer to consume modern energy sources (Li S.C.,2020). They often have a greater awareness of energy conservation, which can reduce HCEs, and are more willing to engage in green consumption and transportation (Yu et al., 2023). However, another previous study indicates that the higher the education level of the population, the more diversified and higher the demand, leading to more HCEs (Li et al., 2019). Increased levels of education are typically associated with higher earnings, leading to an increase in disposable income for households. As a result, the higher the quality of life within a household, the higher the carbon emissions (Han et al., 2023). These studies highlight the significant role of education in HCEs, as well as the importance of strengthening energy-saving, low-carbon, and environmental education.

2.2.3 The age characteristic of household

The age of residents has a significant impact on energy consumption and HCEs. Murray and Mills (2011) suggested that HCEs in the US are correlated with the age of residents. Studies have indicated that the aging characteristics of household populations can reduce HCEs (Yu et al., 2022). Shaped by traditional culture, the elderly tend to have a lower propensity to consume and a stronger sense of thrift, which helps to reduce HCEs (Tong and Zhou, 2020). Besides, Mehmood et al. (2021) found that the seniors age group ≥65 were responsible for the highest HCEs in India. The older people prefer to use traditional and less energy efficient way to meet heating and entertainment demand, rather than the smart and energy saving appliances. Compared with younger adults, older people spend more time at home and need more energy to support their daily lives, which leading to more HCEs (Yagita and Iwafune, 2021). Sun and Lu (2023) believe that the increase in the elderly population exacerbates carbon emissions from healthcare, but overall it leads to a reduction in carbon emissions in other consumer activities. Different age groups have an impact on HCEs in different ways, such as consumption structure level and labour force level, which are complex and diverse (Yu et al., 2023).

2.2.4 Household size

Household size is an important factor affecting HCEs. Large families typically have more consumption expenditure than smaller families, while larger families can benefit from scale effects, which means a sharing mechanism can lead efficient use of goods and services in multi-person households and reduce carbon emissions *per capita* (Yates, 2018). Household members share electrical appliances, tools and equipment, cook together, cool and heat common living spaces and require less individual living space (Ivanova and Büchs, 2020). Empirical studies have shown that smaller households have higher *per capita* HCEs (Lyons et al., 2012; Qu et al., 2013; Underwood and Zahran, 2015; Ala-Mantila et al., 2014; Underwood and Fremstad, 2018; Ellsworth Krebs, 2020; Guo et al., 2022; Yu S.W. et al., 2023). The trend of declining family members in industrialized countries may undermine the benefits from intra-household sharing (Schroder et al., 2015). Hu Z. (2018) analyzed the carbon emissions of Japanese households from 2001 to 2011 and concluded that Japanese household size inhibited the average carbon emissions. Conversely, some studies argue that household size promotes HCEs (Sun Y., 2022; Zhao et al., 2023). If the total population of a region remains stable but family size shrinks, with each family's basic consumption unchanged, this would lead to an increase in HCEs (Shang et al., 2021). Scholars further analyze the impact of household size on direct and indirect HCEs and suggest that the household size increases indirect HCEs (Yu et al., 2022; Meng et al., 2023). Zhang Y.M. (2022) find that household size in Chinese cities has expressed a significant negative effect on indirect *per capita* HCEs, which was much larger than that on direct HCEs.

In 2022, China experienced a negative population growth. Factors such as low birth rates, aging of population, urbanization, and a rising divorce rates have collectively contributed to the continuous reduction in the size of Chinese households (Wang and Zhou, 2021). The acceleration of the aging process has led to a rise in the number of empty-nest families. Pursuing higher education and work-related pressures have resulted in more

young people marrying and having children at a later age. Additionally, delays in the age of first marriage and the increased interval between first marriage and first childbirth have both contributed to an increase in the proportion of one-person and two-person households. The aging of the population and the mobility of population have raised the proportion of empty-nest and single-person households. As a result, these families show reductions in both direct and indirect carbon emissions because they experience income insecurity (empty-nest families, etc.) or youth phase (single-person families and Dink families) that they are unable or unwilling to follow the traditional living pattern.

2.2.5 Household location

The urban-rural attribute of households has a significant positive effect on household carbon emissions (Sun Y, 2022). Urban household carbon emissions are generally higher than those in rural households (Fan et al., 2021). The urbanization process has varying impacts on direct and indirect HCEs (Li et al., 2015). There are obvious differences between urban and rural areas in terms of economic development, population structure, and consumption patterns, and the core factor affecting the differences in *per capita* carbon emissions is *per capita* income (Zhou et al., 2020; Feng et al., 2023). However, current research tends to focus on the accounting of HCEs from either urban or rural areas, neglecting comparative analysis of HCEs from urban and rural household consumption (Li and Wang, 2021).

Limited to availability of data, most scholars study the driving factors of HCEs from a macro perspective, neglecting the effects of micro households' characteristics. The latest research prefers to analyze the impact of household size on HCEs, direct and indirect HCEs, and explore how household size affects the emissions under different income and education levels, but without focusing on the differences under disparate household consumption patterns. As a developing country, there is an imbalance in urban and rural development in China. Moreover, with economic development and income improvement, China's household consumption level increases while the consumption structure changes from survival type to development and enjoyment type, which may increase household carbon emission (Zhang et al., 2020; Han et al., 2023).

This paper explores the regional characteristics of HCEs based on micro-level data of the 2018 China Family Panel Studies (CFPS), which covers the whole country and adopts probability sampling method. On the one hand, it analyzes the disparity in carbon emissions between urban and rural households and explores whether the trend of household size reduction and urbanization process will deepen urban-rural inequality in China. On the other hand, it analyzes whether the households of smaller size have a high-carbon consumption pattern by comparing the differences in the impact of eight categories of household consumption expenditure items, including food, clothing, housing, living supplies and services, transportation and communication, education, culture, and entertainment services, medical care, and other supplies and services. This paper conducts an in-depth analysis of the correlation between household size and HCEs from a structural perspective, providing targeted and differentiated strategies and suggestions for effectively achieving household carbon reduction in the context of the continuous reduction of household size in China, and contributing to the realization of China's "carbon peaking and neutrality" strategy and green development.

3 Research hypotheses

The impact of household size on HCEs is reflected in two aspects: economies of scale within households and changes in the number of households. On one hand, households experience economies of scale, which reduce *per capita* HCEs. Although larger households typically have higher overall consumption expenditures compared to smaller households, resource sharing among household members can lead to cost savings and efficiency improvements. This scale effect can reduce *per capita* carbon emissions (Yates, 2018). As household size increases, members can share energy and electrical appliances such as lights, televisions, computers, and washing machines, thus reducing energy waste and redundancy, and improving energy use efficiency (Ellsworth-Krebs, 2020). Sharing appliances, tools, and equipment, cooking together, and jointly heating and cooling shared living spaces reduce the need for individual living spaces (Ivanova and Büchs, 2020). Larger households can also develop shared lifestyles and consumption habits, such as using transportation collectively, thereby reducing individual carbon emissions and the household's carbon footprint (Underwood and Fremstad, 2018). A decrease in household size can undermine the benefits of internal sharing (Schroder et al., 2015). The trend towards smaller household sizes impacts the resource-sharing effect within households, generally increasing *per capita* consumption. For instance, the sharing degree of residential consumption is typically high, and the reduction in household size likely increases *per capita* residential consumption expenditure (Cao et al., 2019). On the other hand, with a constant population size, a decrease in household size implies an increase in the number of households. If the basic consumption per household remains unchanged, this will lead to an increase in household carbon emissions (Shang Mei, 2021). A significant manifestation of the shrinking household size in China is the rise in the proportion of one-person and two-person households. These households need to purchase more durable goods to meet the needs of their members, indirectly leading to additional energy consumption and carbon emissions. For example, divorces result in two separate households, further increasing consumption in areas like housing, home appliances, and transportation, which generates additional household carbon emissions, even surpassing the carbon emission increase from newborns (UNFPA, 2009). In summary, household size primarily affects household carbon emissions through economies of scale and sharing mechanisms that influence consumption patterns. Based on this, the following research hypotheses are proposed.

Hypothesis 1: Household size has a negative impact on *per capita* HCEs.

Household size affects HCEs through scale effect, Therefore, the impact of household size on direct and indirect HCEs also has a scale effect. Thaiyoong and Maclean (2011) believes that different consumer goods have different scale effects. For example, when a young person leaves his or her parents to live alone, he or she will

incur consumption expenses such as renting a house (or buying a house), buying a car, purchasing household appliances and household commodities. New energy consumption such as lighting and heating will increase direct carbon emissions, while new residential and transportation consumption will increase indirect carbon emissions. Because the demand for housing and transportation has a larger carbon emission coefficient (Qu Jiansheng, 2012; Xiang Huali, 2022), compared with the increase of direct carbon emissions caused by lighting and heating, indirect carbon emissions increased more. It means that the scale effect of indirect carbon emissions is greater than that of direct carbon emissions. Some scholars have pointed out that the impact of household size on indirect HCEs is greater than on direct HCEs (Yu et al., 2022; Meng et al., 2023; Zhang et al., 2023). Therefore, this study proposes the hypothesis 2.

Hypothesis 2: Household size has a negative impact on direct and indirect HCEs, the impact of household size on indirect HCEs is greater than on direct HCEs.

This study further argues that the eight categories of consumer goods that generate indirect HCEs have different scale effect. As household income increases, the household consumption structure also changes, showing a decrease in the proportion of food consumption and an increase in expenditures on transportation, communication, and housing (Han Jun 2023). Different consumption types have varying carbon emission coefficients, with housing having a high emission coefficient (Qu Jian sheng, 2012). Increased housing expenditures will raise household carbon emissions. Household lifestyles are becoming increasingly carbon-intensive (Zhang et al., 2020). Different household sizes have varying proportions of consumption types in their overall consumption, leading to differences in the carbon emission structures among different household sizes (Qinchi, 2015). Xinkuo and Han (2017) found that food, clothing, housing, and communication consumption significantly contribute to urban household carbon emissions in China, and income growth and smaller household sizes mainly increase carbon emissions through these types of consumption. Therefore, this study proposes the hypothesis 3.

Hypothesis 3: The impact of household size on indirect HCEs is heterogeneous in consumption structure and the impact of family size on indirect HCEs from housing, transportation is greater than that of other consumption items.

China, as a developing country, exhibits a dual urban-rural structure. Concurrently, China's rapid urbanization process has increased the urbanization rate from 36.22% in 2000 to 63.89% in 2020. The combined effect of urbanization and shrinking of household size on HCEs is worth exploring. There are significant differences between urban and rural areas in population structure, economic development, *per capita* income, and consumption patterns (Zhou et al., 2020; Feng et al., 2023). Income levels and consumption structures are major factors causing differences in carbon emissions between urban and rural households (Zhang et al., 2019). Urban households generally have higher income and consumption levels than rural households, leading to higher carbon emissions in urban households (Fan et al., 2021). On one hand, rapid urbanization leads to a massive influx of rural populations into cities, with infrastructure development increasing carbon emissions (Satterthwaite, 2009); on the other hand, urban consumption levels are higher, with stronger consumption capabilities, more diverse consumption choices, and more integrated consumption patterns, continuously increasing urban household energy consumption. Therefore, this study proposes the hypothesis 4.

TABLE 1 Chinese carbon emission factors.

Types	Factors
Raw coal	1.7t-CO2/t
Cleaned coal	2.21t-CO2/t
Other cleaned coal	0.7t-CO2/t
Coke	2.53t-CO2/t
Coke oven gas	6.18t-CO2/10000m3
Crude oil	2.91t-CO2/t
Gasoline	2.85t-CO2/t
Kerosene	2.94t-CO2/t
Gas oil	3.03t-CO2/t
Fuel oil	3.09t-CO2/t
Liquefied petroleum gas	3.03t-CO2/t
Nature gas	20.93t-CO2/10000m3

Hypothesis 4: The impact of household size on urban household carbon emissions is greater than that in rural areas.

4 Materials and methods

4.1 Data sources

The data of this research comes from the family economy and relationship databases of China Family Tracking Survey (CFPS) database. The survey, conducted by the China Social Science Survey Center of Peking University, takes households as a sample, and adopts the probability sampling methods of proportional population size, implicit stratification and multi-stage, which has certain authority. According to the research content, this paper selects the household consumption expenditure items such as clothing, food, shelter, transportation, and energy in the database to calculate HCEs. After cleaning, the data of 9,090 households in 2018 were finally selected.

4.2 Measurement of household consumption carbon emissions

In the Kyoto Protocol, an international agreement, there are six kinds of greenhouse gases to be controlled, including carbon dioxide, methane, etc. The emissions of these gases are called carbon emissions (IPCC, 2014). However, due to the largest proportion of carbon dioxide emissions in daily life, carbon dioxide emissions are regarded as carbon emissions, so this paper

takes carbon dioxide emissions as carbon emissions, and the total carbon dioxide emissions generated by various consumption behaviors in households are called HCEs. HCEs can also be divided into direct and indirect HCEs according to their sources. Direct HCEs come from the use of main cooking fuel, electric energy, and heat energy, while indirect HCEs come from eight categories of consumption expenditure.

4.2.1 Direct household consumption carbon emissions

Refer to the calculation method of Sun Yue (2022), direct household consumption carbon emission is the sum of household fuel carbon emission, electricity carbon emission and heating carbon emission. This paper uses the IPCC inventory method to estimate direct carbon emissions and for improving the measurement accuracy, the Chinese carbon emission factors (Table 1) were finally selected for calculation (Liu et al., 2013).

(1) Household fuel carbon emissions. Firstly, according to the CFPS household economy database, the fuel type is determined by the variable of "main fuel for cooking"; Secondly, the specific energy consumption Q_i is calculated based on the household fuel cost of the household in the previous year and the annually average market price of main fuels. Thirdly, determine the carbon emission factor and calculate the carbon emission according to formula (1). The specific process follows the formula (1).

$$C_d = Q_i \times f_i \tag{1}$$

Where C_d represents carbon emissions of energy in once (unit: kg); indicates the type of energy; Q_i represents the physical quantity of the i energy consumption (unit:kg/km3); f_i represents the carbon emission factor of the i energy.

(2) Household electricity carbon emissions. The calculation is similar to the method above. Firstly, the electricity consumption Q_e is calculated from the average annual price of residential electricity, and then the calculate direct carbon emission according to the carbon emission factors. Refer to the calculation method of Zhu Qin (2010), the specific formula (2) is as follows.

$$C_e = Q_e \times SCC \times 2.46 \tag{2}$$

Where C_e represents carbon emissions from household electricity (unit: kg); Q_e indicates household electricity consumption (unit: kw·h); *SCC* indicates Standard coal consumption rate of thermal power generation (unit: kg standard coal/kw·h); 2.46 means that each kilogram of standard coal burned will release 2.46kgCO_2.

(3) Household heating carbon emissions. The heating capacity Q_h of residents is calculated according to the residents' heating cost and the heating price of 44 RMByuan/GJ. Since there is basically no carbon emission in the heating process of residential households, this paper only takes production stage in consideration. Calculation is according to formula (3).

$$C_h = Q_h \times 34.12 \times 2.46 \tag{3}$$

Where C_h represents the household heating carbon emissions (unit: kg); Q_h represents physical amount of household thermal energy consumption (unit: GJ); 34.12 is the standard coal conversion coefficient that commonly used in China, which means that 1 GJ heat is produced needs 34.12 kg of standard coal consumed (unit: kg standard coal/kw·h); 2.46 Ibid.

TABLE 2 Household carbon emission coefficient of consumer goods.

Type	Coefficients
Food	0.095 kgCO_2/yuan
Clothing	0.126 kgCO_2/yuan
Shelter	0.192 kgCO_2/yuan
Daily necessities and services	0.158 kgCO_2/yuan
Transportation and communication	0.159 kgCO_2/yuan
Education, culture and entertainment services	0.160 kgCO_2/yuan
Medical care	0.177 kgCO_2/yuan
Other supplies and services	0.064 kgCO_2/yuan

4.2.2 Indirect household consumption carbon emissions

Household indirect carbon emissions were measured according to input-output method and consumer lifestyle method. Refer to Qu Jiansheng (2012), household expenditures that generate indirect carbon emissions are divided into eight categories, including food, clothing, shelter, daily necessities and services, transportation and communication, education, culture and entertainment services, medical care, and other supplies and services. The carbon emission coefficients of the eight categories of household expenditures are shown in Table 2. The calculation formula (4) is as follows.

$$C_m = Ii_c \times Ci_c \tag{4}$$

Where C_m represents the household indirect carbon emissions (unit: kg); Ii_c represents annual household expenditure on various consumer goods (unit: ¥); Ci_c indicates carbon emission coefficient of household consumer goods (unit: kgCO_2/yuan).

4.3 Model setting

According to the STIRPAT model (Dietz and Rosa, 1994; York et al., 2003), this paper takes the household as research object to establish the household environmental pressure model (formula 5). Specific linear regression model is as follows.

$$\ln I = \ln \alpha + b\ln P_i + c\ln A_i + d\ln X_i + \ln \varepsilon_i \tag{5}$$

Where I is household consumption carbon emissions; P_i represents household demographic characteristics; A_i indicates household economic characteristics; X_i represents education level; ε_i is random error term.

Given the comprehensive consideration of the factors affecting household carbon emissions, this paper takes *per capita* household carbon emissions as the explained variable of model (5), family size as the core explanatory variable, and selects the gender (Ying et al., 2023), age (Yu et al., 2022), *per capita* income (Nair et al., 2019), urban and rural attributes (Suling Feng et al. ,2023), and education

TABLE 3 Definition of model variables.

Type	Name	Code	Meaning
Explained variables	Household *per capita* consumption carbon emissions	*perc*	Direct (indirect) household carbon emissions/household population
	Household *per capita* direct carbon emissions	*d_perc*	
	Household *per capita* indirect carbon emissions	*i_perc*	
Explanatory variable	Family size	*size*	-
Control variables	Gender of household head Per capita household income	*gen*	Female = 0, Male = 1
	Age of head of household	*age*	-
	Per capita household income	*perin*	Net household income/family size
	Urban and rural attributes	*ur*	Rural registration = 0, urban registration = 1
	Educational level	*edu*	Illiteracy/semi-illiteracy = 0, primary school = 1, junior high school = 2, high school = 3, junior college = 4, university = 5, master's = 6, Doctor's = 7

level of the household (Zhang et al., 2022) as the control variables, as shown in Table 3. In most studies, it is usually linearized by taking a natural logarithm on both sides in solving the problem of heteroscedasticity and conducting regression analysis (Yu et al., 2023). In this paper, the logarithm of the explained variables, explanatory variable, the variable of age and *per capita* household income is taken. The baseline model describes the influence of household characteristics on HCEs (Formula 6), which is estimated by ordinary least square method (OLS).

$$lnperc = ln\alpha + b_1 lnsize + b_2 gen + b_3 lnage + clnperin + d_1 edu + d_2 ur + ln\varepsilon_i \quad (6)$$

The definition of household size is the number of members in a household which clearly explained in the User Manual of the Chinese Family Tracking Survey. Only those who are directly or indirectly related by marriage, blood or adoption are defined as family members. And family members include those who live at home and those who live outside but have financial ties to family members. The reason why the head of household is used is that the head of household plays a significant role in household consumption decisions and patterns, and the age and gender of the head of household have a crucial impact on the scale and structure of household energy consumption (Golley J et al., 2008).

Table 4 is a descriptive statistical analysis of variables. The maximum and minimum values of *per capita* HCEs, direct HCEs and indirect HCEs, and *per capita* household income differ greatly, indicating that there are large differences among households. The largest household size was 17, with an average of 3.479, higher than the national average level in 2018; the average age of the head of household is 51.26 years old, indicating that the head of household is mainly middle-aged and elderly. Urban households accounted for 61% of the total sample. The average education level of the head of household is close to the level of junior high school. The reason for the low education level of the head of household may be that the head of household is older. The head of household over the age of 50 may have been born before 1980, when China's education level was not high.

5 Results

5.1 Accounting results of household carbon emissions

The calculation result shows that the indirect HCEs are greater than the direct HCEs. In 2018, the average HCEs was 1.35 tons, of which the average direct HCEs was 0.38 tons, and the average indirect HCEs was 0.97 tons. The *per capita* HCEs is 0.51 tons, of which the *per capita* direct HCEs is 0.13 tons, and the *per capita* indirect HCEs is 0.38 tons.

5.1.1 Scale and composition of *per capita* carbon emission of urban and rural households

As shown in Table 5, the level of urban HCEs is higher than rural. The HCEs of urban and rural is 1.45 tons and 1.22 tons respectively, and the per HCEs of urban is greater than rural. The *per capita* HCEs of urban and rural were 0.57 and 0.42 tons, The *per capita* HCEs of urban were greater than rural households; The *per capita* direct HCEs and *per capita* indirect HCEs of urban are greater than those of rural. However, the proportion of *per capita* direct HCEs of urban HCEs (24.6%) is lower than that of rural (28.5%). It is worth mentioning that there are obvious differences in the scale and composition of HCEs in urban and rural areas, which are caused by the differences in lifestyle, energy structure, economic development level and infrastructure between urban and rural areas. The proportion of *per capita* direct HCEs of rural households is slightly higher than that of urban households, mainly because of the simple energy structure in rural that relies on traditional energy sources for heating and cooking.

5.1.2 Composition of per capita HCEs by different household size

According to the accounting data, this paper found that the smaller family size, the higher the *per capita* direct and indirect HCEs. In one-person household, the HCEs direct and indirect HCEs are 2.46 and 9.40 tons/person respectively, while those in an eight-person household are 0.53 and 0.73 tons/person respectively, and the emission of the one-person household is about 4.64 and

TABLE 4 Descriptive statistics of variables.

Code	N	Minimum	Maximum	Average value	Standard deviation
perc	9,090	186.96472	1180826.3671	5152.657768	6086.753192
d_perc	9,090	13.83596	26900.32421	1340.601634	1543.522187
i_perc	9,090	0	107544.3200	3812.056133	5685.954033
size	9,090	1	17	3.479	1.8169
gen	9,090	0	1	0.50	0.5
age	9,090	17	96	51.26	15.491
perin	9,090	300	5660000	35318.65589	101835.8328
ur	9,090	0	1	0.61	0.487
edu	9,090	0	7	1.92	1.434

TABLE 5 The HCEs of urban and rural (unit:tCO_2).

Household carbon emission	Urban	Rural
HCEs	1.45	1.22
per capita HCEs	0.57	0.42
per capita direct HCEs	0.14	0.12
per capita indirect HCEs	0.43	0.30
proportion of *per capita* direct HCEs	24.6%	28.6%

12.87 times than the eight-person household. Figure 1 show that with the reduction of household size, the proportion of indirect HCEs *per capita* increases, while the proportion of direct HCEs *per capita* decreases.

5.1.3 Characteristics of household size and HCEs in China's provinces

This study matched the sample data to provinces, and then calculated the average values of household size, *per capita* HCEs, *per capita* direct HCEs, and *per capita* indirect HCEs in provinces (see Figures 2, 3, 4, 5).

Figure 2 shows that Heilongjiang, Liaoning, Jilin, Xinjiang, Tibet, Ningxia and Beijing are provinces with small family sizes. Figure 3 shows that Heilongjiang, Liaoning, Jilin, Xinjiang, Tibet, Ningxia, Hainan, Jiangsu and Zhejiang are the regions with high levels of *per capita* HCEs and these provinces are mainly the western regions and the economically developed eastern regions. The provinces with smaller household size partially overlap with those with higher *per capita* HCEs, which confirms that there may be a negative correlation.

Figure 4 show that the province of Heilongjiang, Liaoning, Jilin, Xinjiang, Ningxia, Qinghai, Shanxi, Shaanxi have higher *per capita* direct HCEs. These provinces are concentrated in northern China, with high latitude and relatively low temperature. They need more energy for heating in winter, thus bringing more energy consumption and direct HCEs. Figure 5 show that the provinces with high household indirect carbon emissions are Tibet, Ningxia, Jilin, Xinjiang, Qinghai, Hainan, Jiangsu, Zhejiang and Shanghai. The high indirect HCEs in Tibet, Ningxia, Xinjiang and Qinghai

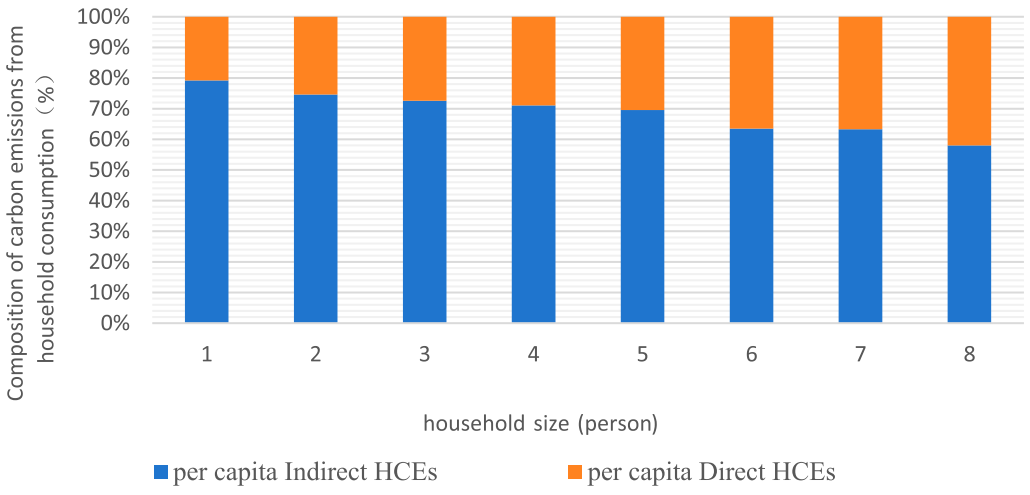


FIGURE 1
Composition of *per capita* HCEs by different household size.

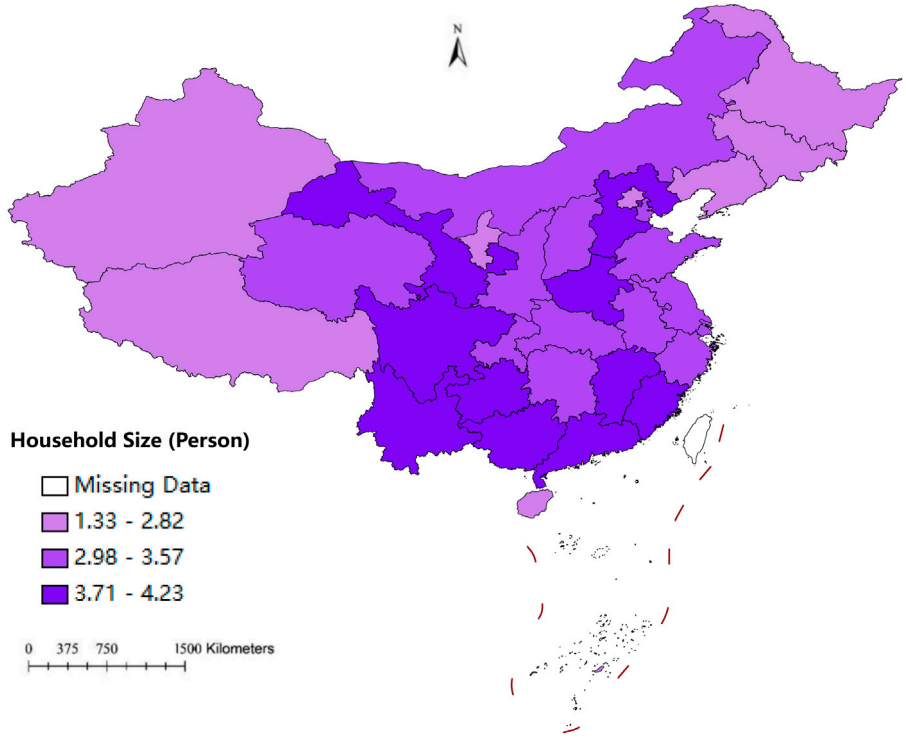


FIGURE 2
The average household size of provinces in China.

may be related to the small number of survey data samples in the database, and there is uncertainty in the data. Jiangsu, Shanghai and Zhejiang are economically developed regions with high income levels, so indirect HCEs related to consumption are relatively high.

5.2 The correlation analysis

As shown in Table 6, the absolute values of correlation coefficients among all explanatory variables are not higher than 0.5, and VIF is not higher than 1.6, indicating that there is no multicollinearity problem among explanatory variables.

5.3 The results of empirical analysis

5.3.1 The impact of household size on *per capita* HCEs

This study uses OLS to analyze the relationship between household size and *per capita* HCEs.The regression results are shown in Table 7. Column (1) in the table is the estimation result without controlling variables, and column (2) to column (6) are regression results considering *per capita* household income, age and gender of household head, urban and rural attributes, and education level, respectively.

The results show that the coefficients of household size from column (1) to column (6) are significantly negative, which means that household size has a significant negative impact on *per capita* HCEs, that is, the smaller the family size, the higher the *per capita* HCEs. Hypothesis 1 is verified. The absolute value of the coefficient of household size is greater than the control variable, indicating that household size is the primary factor affecting *per capita* HCEs. Other variables in order of influence degree are *per capita* household income, age of head of household, urbanization and education level.

There is a significant positive correlation between *per capita* household income and *per capita* HCEs. The reason is that with the increase of household income, the level of household consumption has improved. In addition, people pursue high-quality, diversified and refined consumption, which promotes the increase of carbon emissions from household consumption (Weber et al., 2008; Nair et al., 2019; Hartono, 2023).

The age of household head has a significant negative effect on *per capita* HCEs, which is consistent with Tong Yufen (2020) and Yu et al. (2022). The reason may be that with the growth of age, the consumption willingness of household head decreases, the awareness of saving becomes stronger, and more attention is paid to environmental protection, energy conservation and emission reduction, thus reducing the household's carbon emissions. The regression results of gender are not significant, indicating that gender of household head has no significant impact on household energy consumption patterns. The regression coefficient of urban and rural attributes is significantly positive, which means that in the process of urbanization, the urban lifestyle of households and the increase of urban families will increase the *per capita* HCEs. Education level has a significant positive impact on household carbon emissions, and the reason may be that household

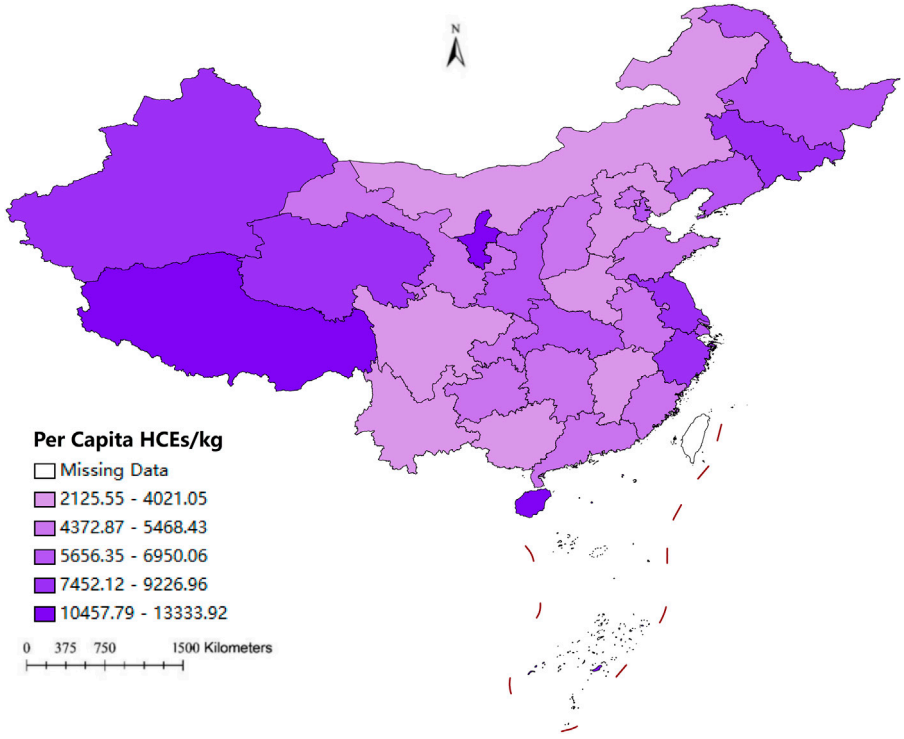


FIGURE 3
The average *per capita* HCEs of provinces in China.

with higher education income more and desire a higher quality of life, and the relative increase in consumption demand will increase HCEs (Li et al., 2019).

5.3.2 The impact of household size on direct and indirect HCEs

As shown in Table 8, household size has a significant negative impact on *per capita* direct HCEs. Larger households can share energy demands (such as heating, cooling, and lighting), thereby benefiting from economies of scale, which result in relatively lower *per capita* direct carbon emissions. In columns (2) to (6), by gradually controlling the variables of *per capita* household income, age and gender of the head in family, urban and rural attributes, and education level, the results remain stable except the gender. The coefficients of household size are −0.5916, −0.5832, −0.5821, −0.5825, −0.5613, and −0.5604, respectively. Although the absolute value of the coefficient decreases with the introduction of control variables, it remains higher than those of other variables. The influence of other variables, in descending order of magnitude, are *per capita* household income, urbanization, education level, and age of the household head.

As shown in Table 9, household size has a significant negative influence on *per capita* indirect HCEs. These results are consistent with the results of Underwood and Fremstad (2018) and Guo et al. (2022). The absolute value of the coefficient for the impact of household size on *per capita* indirect HCEs (0.9279) is greater than that on *per capita* direct HCEs (0.5604), indicating that household size has a larger impact on indirect HCEs than on direct HCEs. Hypothesis 2 is thus confirmed. The absolute value of the household size coefficient also exceeds that of other variables, indicating that household size is a key factor influencing indirect HCEs. In descending order of magnitude, the other influential factors are *per capita* household income, age of the household head, urbanization, and education level. This ranking is consistent with that for HCEs indicating that indirect HCEs dominate the HCEs and exhibit a similar trend.

5.4 The robust test

This study further verifies the robustness of the baseline regression results by employing alternative regression methods and replacing variables. The Generalized Least Squares (GLS) method is applied to further eliminate heteroscedasticity and correct the model to obtain more efficient parameters. As shown in Table 10, the positive and negative of the coefficients remains consistent with the baseline regression results from the OLS method.

In this study, the number of books in the household is used as a substitute for the household education level variable (Cong et al., 2023). Upon cleaning the sample data, it was found that out of 9,090 samples, 3,548 samples had a value of "0," and 85 samples were marked as "not filled" or "unknown". By excluding the "not filled" or "unknown" samples, we obtained 9,005 valid samples. For these 9,005 samples, a value of 1 was uniformly added before taking the logarithm for the OLS regression. The results are presented in

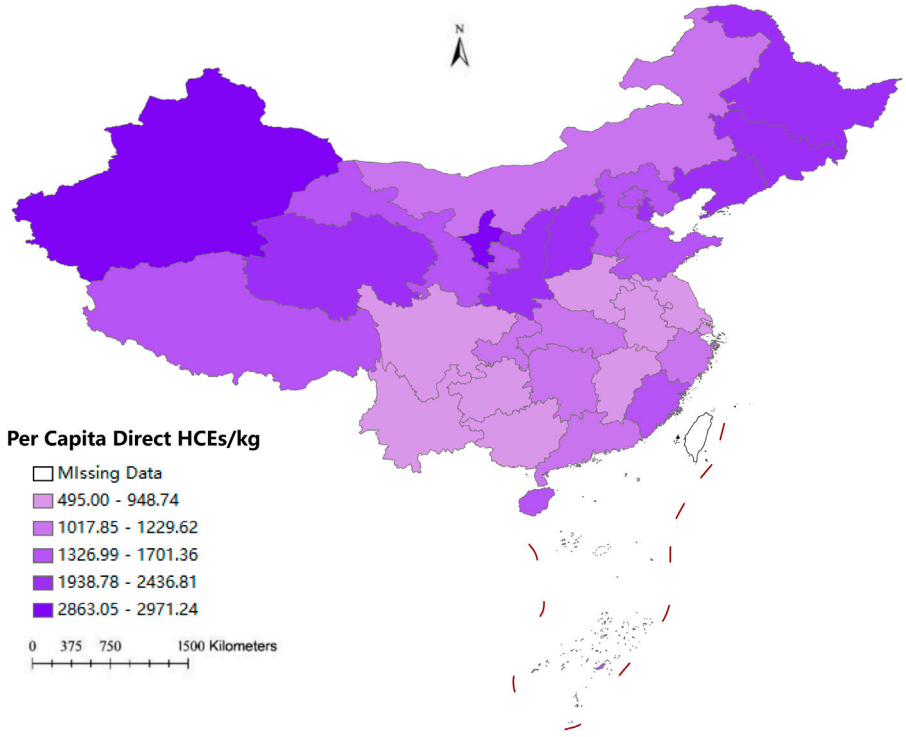


FIGURE 4
The average *per capita* direct HCEs of provinces in China.

Table 11. The positive and negative of the coefficients remains consistent with the baseline regression results.

5.5 Heterogeneity analysis

5.5.1 Household consumption expenditure analysis

According to the classification of household consumption expenditure above, the household expenditures that produce indirect HCEs mainly fall into eight categories: food (*food*), clothing (*dress*), shelter (*house*), daily necessities and services (*daily*), transportation and communication (*trco*), education-culture and entertainment services (*eec*), medical care (*med*) and other supplies and services (*other*). Chinese households are experiencing changes in consumption patterns, most notably an increase in the proportion of expenditure on housing-related consumption and a decrease in the proportion of expenditure on food-related consumption. This study analyzes the impact of household size on HCEs resulting from eight categories of consumption expenditure, exploring the relationship between household size and household consumption patterns.

As shown in Table 12, all coefficients are negative and significant at the 1% level, The findings demonstrate that household size has a significant negative impact on *per capita* HCEs across all eight expenditure categories. The results further confirm the existence of economies of scale in household carbon emissions and suggest that the benefits of different categories of resources can be shared among family members. In the eight categories of household expenditures, the coefficients are as follows: food (−0.2231), dress (−0.0967), housing (0.5131), daily necessities (−0.0643), transportation and communication (−0.1982), education, culture, and entertainment (−0.1107), healthcare (−0.0092), and other expenses (−0.0789). The top4 impact is observed in housing, food, and transportation and communication, while the smallest is in healthcare. The significant carbon emission coefficients for housing, food, and transportation and communication expenditures indicate that smaller households have higher demands for housing, food, and transportation, leading to higher carbon emissions. Smaller households exhibit a consumption pattern with higher carbon emissions. Hypothesis 3 is thus validated.

Comparing the driving factors of each consumption category reveals that household size is not the key factor for all consumption items. Food expenditure is primarily influenced by *per capita* household income and urbanization, while dress expenditure is mainly affected by household size and household income. Housing expenditure is primarily influenced by household income and household size. Daily necessities are mainly influenced by age and household size. Transportation expenditure is primarily affected by household income and gender. Education, culture, and entertainment expenditure are mainly influenced by household size and household income. Healthcare expenditure is affected by urbanization and age, while other goods and services expenditure is influenced by urbanization and household size. Identifying these factors can help formulate targeted emission reduction measures.

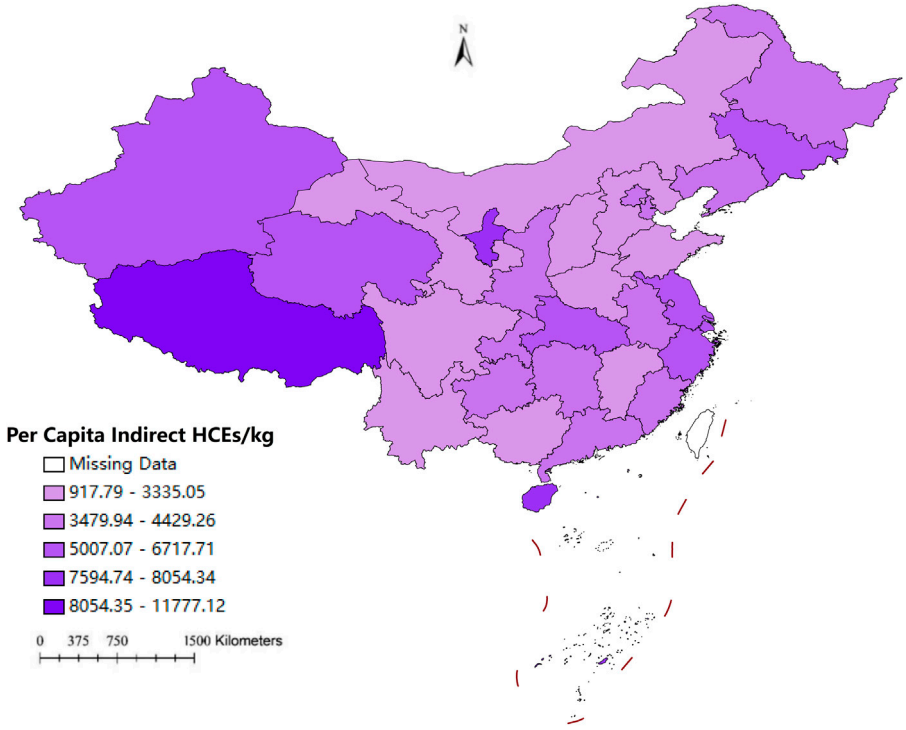


FIGURE 5
The average *per capita* indirect HCEs of provinces in China.

TABLE 6 Correlation coefficients of explanatory variables.

	lnsize	*lnperin*	*gen*	*lnage*	*edu*	*ur*
lnsize	1.0000					
lnperin	−0.1304	1.0000				
gen	0.0135	0.0093	1.0000			
lnage	0.1499	−0.2454	−0.0022	1.0000		
edu	−0.1228	0.4426	0.0092	−0.4725	1.0000	
ur	−0.1158	0.1700	0.0013	−0.0511	0.1063	1.0000
VIF	1.04	1.28	1.00	1.30	1.51	1.04

5.5.2 Urban and rural analysis

From Table 13, it can be seen that household size has a significant negative impact on *per capita* carbon emissions for both rural and urban households. The elasticity coefficients of household size on *per capita* carbon emissions are greater for urban households than for rural households. This is primarily due to differences in lifestyle and purchasing power between urban and rural households. Compared to rural households, urban households have a more modern lifestyle, greater purchasing power, and higher frequency of transportation. It may also be related to the relatively traditional lifestyle of rural residents, who are more likely to live with older generations, resulting in larger household sizes. Additionally, *per capita* household income has a greater impact on urban households than on rural ones. The effects of the household head's age and education level are smaller in urban households compared to rural households. This collectively indicates that rural households are more traditional and frugal. Higher education levels among household heads are more beneficial in raising energy-saving and environmental awareness, thereby reducing HCEs. Hypothesis 4 is thus confirmed.

6 Discussion

The factors affecting household carbon emissions include two aspects: household consumption patterns and household demographic characteristics. Scholars have extensively studied the impact of household size on carbon emissions under different income and education levels. This article analyzes the impact of changes in household size on HCEs from the perspective of family consumption structure and argues that families with smaller sizes tend to favor high-carbon emission consumption items, and the effects show urban-rural heterogeneity. This paper contributes to the study of household carbon emissions and is subject to three potential weaknesses.

Currently, the methods of Structural Factor Analysis and Regression Analysis are mainly used in academia for quantitative analysis of the impact of household characteristics on HCEs. The Structural Factor Analysis is well-theoretically grounded in the selection of driving factors (Shi, 2023). Regression Analysis is primarily based on the STIRPAT model and the STIRPAT model can be used to analyze various factors that cause disproportionate changes in environmental pressure (York et al., 2003), and it is

TABLE 7 The result of baseline regression.

	(1)	(2)	(3)	(4)	(5)	(6)
lnsize	−0.9187*** (0.0131)	−0.8500*** (0.0120)	−0.8372*** (0.0120)	−0.8372*** (0.0120)	−0.8273*** (0.0121)	−0.8248*** (0.0120)
lnperin		0.2936*** (0.0067)	0.2798*** (0.0067)	0.2798*** (0.0067)	0.2707*** (0.0069)	0.2437*** (0.0074)
lnage			−0.1805*** (0.0207)	−0.1805*** (0.0201)	−0.1803*** (0.0206)	−0.0892*** (0.0225)
gen				−0.0031 (0.1310)	−0.0032 (0.1310)	−0.0041 (0.1300)
ur					0.1171*** (0.0137)	0.1134*** (0.0056)
edu						0.0548*** (0.0056)
constant	9.1701*** (0.0162)	6.1791** (0.0699)	7.0031* (0.1174)	7.0045* (0.1175)	7.0134* (0.1171)	6.8209* (0.1181)

Note: *** (**/*) indicates that the result is statistically significant at 1% (5%/10%) level (same as the table below).

TABLE 8 Regression results of household size and *per capita* direct HCEs.

	(1)	(2)	(3)	(4)	(5)	(6)
lnsize	−0.5916*** (0.0156)	−0.5832*** (0.0157)	−0.5821*** (0.0159)	−0.5825*** (0.0159)	−0.5613*** (0.0158)	−0.5604*** (0.0157)
lnperin		0.0359*** (0.0088)	0.0346*** (0.0090)	0.0344*** (0.0090)	0.0149*** (0.0090)	0.0050*** (0.0090)
lnage			−0.0159** (0.0272)	−0.0159** (0.0272)	−0.0166** (0.0269)	0.0169** (0.0296)
gen				−0.0321 (0.1730)	−0.0318 (0.1710)	0.0315 (0.1710)
ur					0.2526** (0.0179)	0.2510** (0.0179)
edu						0.0200*** (0.0073)
Constant	7.4531** (0.0193)	7.0878* (0.0915)	7.1608* (0.1543)	7.1465* (0.1545)	7.1656* (0.1528)	6.0952* (0.1549)

TABLE 9 Regression results of household size and *per capita* indirect HCEs.

	(1)	(2)	(3)	(4)	(5)	(6)
lnsize	−1.0631*** (0.0175)	−0.9604*** (0.0156)	−0.9380*** (0.0156)	−0.9379*** (0.0156)	−0.9312*** (0.0156)	−0.9279*** (0.0156)
lnperin		0.4412*** (0.0090)	0.4173*** (0.0089)	0.4173*** (0.0089)	0.4111*** (0.0090)	0.3761*** (0.0096)
lnage			−0.3137* (0.0267)	−0.3137* (0.0267)	−0.3140* (0.0267)	−0.1953* (0.0292)
gen				−0.0081 (0.1170)	−0.0082 (0.1170)	−0.0093 (0.1169)
ur					0.0802** (0.0177)	0.0746** (0.0177)
edu						0.0710*** (0.0072)
constant	8.8267** (0.0216)	4.3324* (0.0906)	5.7644* (0.1517)	5.7680* (0.1519)	5.7739* (0.1520)	5.5249* (0.1530)

widely applied in the study of driving factors for carbon emissions. Although the model has some subjectivity in the selection of variables, one of the advantages of the STIRPAT model is its flexibility, allowing as it does for the adding, modification, and decomposition of related influencing factors (Khan et al., 2020).

The input-output method and consumer lifestyle approach are often used to measure indirect HCEs. There is a certain lag when calculating carbon emissions by input-output method, and it may be impossible in accounting because of incomplete input-output tables for some years (Wang et al., 2019). The data used in this paper is 2018, and there is no input-output table for this year, so this paper uses the consumer lifestyle approach to calculate. This method often calculates indirect HCEs by multiplying the amount of residents' consumption by the corresponding carbon emission coefficients. The emission coefficient of consumption amount is fixed and static, without considering account changes in technological progress. If technological progress reduces the prices of consumer goods, the quantity of consumer products may increase even if the amount spent on consumption remains unchanged. So, this method ignores the real rebound effect in consumption, making it difficult to indicate the actual consumption volume of residents. In addition, the coefficients of energy consumption and other consumption activities should be adapted to local conditions. Although the coefficients used in this paper have adjusted based on China's consumption characteristics (Qu et al., 2013), they do not reflect

TABLE 10 Regression results based on GLS.

	lnperc	lnd_perc	lni_perc
lnsize	−0.8248*** (0.0120)	−0.5604*** (0.0157)	−0.9279*** (0.0000)
lnperin	0.2437*** (0.0074)	−0.0050*** (0.0097)	−0.3761*** (0.0096)
lnage	−0.0892*** (0.0225)	−0.0169 (0.0296)	−0.1953*** (0.0292)
gen	−0.0041 (0.0130)	−0.0093 (0.0654)	−0.8248 (0.0169)
ur	0.1134*** (0.0136)	−0.2510*** (0.0179)	0.0746*** (0.0177)
edu	0.0548*** (0.0056)	−0.0200*** (0.0073)	0.0710*** (0.0072)
constant	0.8209*** (0.1181)	0.7952*** (0.1549)	5.5249*** (0.1530)

TABLE 11 OLS regression results by replacing variables.

	lnperc	lnd_perc	lni_perc
lnsize	−0.8359*** (0.0122)	−0.5873*** (0.0159)	−0.9358*** (0.0160)
lnperin	0.2679*** (0.0069)	0.0084*** (0.0090)	0.4105*** (0.0091)
lnage	−0.1769*** (0.0207)	−0.0062*** (0.0269)	−0.3229*** (0.0271)
gen	−0.0069 (0.0131)	−0.0256 (0.0170)	−0.0127 (0.0172)
ur	0.1053*** (0.0141)	0.2057*** (0.0183)	0.0808*** (0.0185)
lnbook	0.0160*** (0.0034)	0.0511*** (0.0044)	0.0044 (0.0045)
constant	7.0108 (0.1175)	7.1402 (0.1526)	5.8102 (0.1538)

the differences of household location. Carbon emission calculation model should be more in line with local production technology level and household consumption characteristics.

Zhang et al. (2023) utilized the 2018 China's Urban Household Income and Expenditure Survey dataset to analyze the impact of household structure changes on carbon emissions. However, the China's Urban Household Income and Expenditure Survey dataset only includes urban household samples, which cannot be compared with rural areas. This study employs the 2018 China Family Panel Studies (CFPS) data, which surveyed a sample of 14,218 households. After cleaning and excluding invalid samples, the final sample size is 9,090. Conducted by the China Social Science Survey Center at Peking University, the CFPS is a comprehensive and nationwide social tracking survey project. And it considers the family as a sample unit, collecting a wide range of data and includes a complete variety of survey questionnaires (Sun Y., 2022). Therefore, this paper uses multidimensional data from the database, including household demographics, economics, and education, and examines the full picture of urban and rural household carbon emissions through household consumption expenditure items related to clothing, food, housing, transportation, and energy, etc. Among the 9,090 samples, the sample size of Tibet, Xinjiang, Ningxia, Qinghai and other provinces is single digit. For instance, there are only 3 samples in the Tibet, with an average household size of 1.3 people, which is the lowest among all provinces. The average household size in Tibet in 2020 was 3.19, the highest in China (The Seventh National Population Census, 2020). A small sample size cannot accurately reflect the regional situation and may lead to uncertainty in the empirical analysis results.

Chen L., et al. (2022) explore the spatial relationship between urbanization and urban household carbon emissions in Chinese cities at the prefecture level and above, revealing the spatiotemporal characteristics of urban residents' carbon emissions. This paper, based on cross-sectional data, discusses the differences in carbon emissions between urban and rural residents in China but has not analyzed the annual changes in household carbon emissions and their influencing factors. In the future, we will collect data from more years to track the spatiotemporal evolution of China's HCEs and driving factors. Liu (2023), based on the analysis of British household data, believes that compared to household income, lifestyle-related factors have a greater impact on household carbon emissions. And Liu (2023) specified how the concept of lifestyle is associated with housing fuel using emissions and motor emissions and evaluated whether the living area and the number of cars owned are the reflection of energy-saving lifestyles. Although this study has focused on the structural changes in household consumption, it cannot determine whether the family's lifestyle tendencies are energy-saving. In the future, this paper will adopt a database that includes more information on family lifestyles to

TABLE 12 The effect of household size on the different expenditure categories.

	food	dress	house	daily	trco	eec	med	other
lnsize	−0.2231*** (0.0204)	−0.0967*** (0.0156)	−0.5131*** (0.0276)	−0.0643*** (0.0365)	−0.1982*** (0.0239)	−0.1107*** (0.0387)	−0.0092*** (0.0349)	−0.0789*** (0.0338)
lnperin	−0.304*** (0.0124)	−0.0525*** (0.0154)	−0.9747* (0.0277)	0.0195* (0.0212)	0.4111 (0.0144)	0.0416* (0.0234)	−0.0524** (0.0221)	−0.0188* (0.0205)
lnage	−0.0430* (0.0382)	0.0737** (0.0475)	−0.308** (0.0516)	0.0732** (0.0687)	−0.0136** (0.0446)	−0.0199** (0.0732)	0.0644** (0.0653)	0.0416** (0.0632)
gen	0.0051 (0.221)	0.0122** (0.0279)	−0.0197** (0.0289)	0.0042** (0.0394)	−0.27996** (0.0258)	−0.0274** (0.0418)	−0.0164** (0.0377)	0.0376** (0.0365)
ur	−0.2555** (0.0232)	−0.0130 (0.2886)	−0.0160** (0.0313)	−0.0459** (0.0414)	−0.0195 (0.2710)	0.0129** (0.0439)	−0.0848** (0.0396)	−0.0935** (0.0384)
edu	−0.0053*** (0.0094)	0.0072*** (0.0117)	−0.0031*** (0.0127)	0.0045 (0.1687)	0.0038* (0.1110)	0.0064*** (0.0179)	−0.0122*** (0.0161)	−0.0019*** (0.0156)
Const-ant	8.0527 0.1990	6.0752 (0.2475)	7.3413 (0.2691)	6.0527 (0.3556)	6.4742 (0.2328)	6.8806 (0.3768)	6.9885 (0.3398)	3.8849 (0.3294)

TABLE 13 The impact of household size on HCEs in urban and rural areas.

	Rural			Urban		
	lnperc	*lnd_perc*	*lni_perc*	*lnperc*	*lnd_perc*	*lni_perc*
lnsize	−0.7112*** (0.0197)	−0.4916*** (0.0265)	−0.8628*** (0.0251)	−0.8392*** (0.0152)	−0.5554*** (0.0194)	−0.9589*** (0.0199)
lnperin	0.2503*** (0.0115)	0.0053 (0.1557)	0.3884*** (0.0147)	0.2806*** (0.0086)	0.0171 (0.0110)	0.4218*** (0.0113)
lnage	−0.2844*** (0.0374)	−0.1465*** (0.0505)	−0.4359*** (0.0478)	−0.1310*** (0.0245)	0.0456 (0.0323)	−0.2532*** (0.0320)
gen	−0.0020 (0.0219)	−0.0083 (0.0296)	0.0039 (0.0286)	0.0105 (0.0162)	−0.0038 (0.0206)	0.0153 (0.0212)
edu	−0.0195** (0.0077)	−0.0338*** (0.0104)	−0.0152 (0.0099)	−0.0020 (0.0057)	−0.0034 (0.0072)	0.0023 (0.0075)
constant	7.6381*** (0.2121)	7.8719*** (0.2895)	6.4524*** (0.2709)	6.8473*** (0.1409)	7.1722*** (0.1796)	5.5241*** (0.1845)
N	3,508	3,508	3,508	5,582	5,582	5,582

delve into the impact of Chinese family lifestyles on household carbon emissions.

7 Conclusion and policy implications

Based on the CFPS (China Family Panel Studies) household data, this paper explores the impact of family size on total household carbon emissions, direct and indirect household carbon emissions, and especially analyzes the heterogeneity of urban and rural structure and household consumption structure.

Firstly, our empirical results have proved that the negative effect of household size on indirect HCEs *per capita* (−0.9279) was greater than that of direct HCEs (−0.5604). On the contrary, household income and education level are positively correlated with household carbon emission, while household aging characteristics are negatively correlated with the emissions. The effect of household size is higher than that of household income, aging, and education level.

Secondly, from the perspective of urban and rural structure, the level of *per capita* carbon emission among urban households (−0.8392) is higher than that of rural households (−0.7112), indicating that the rapid urbanization in China and household size miniaturization increase the imbalance of carbon emissions between urban and rural areas, and have a "superimposed effect" on HCEs, which is not conducive to achieve the target of carbon peaking and neutrality.

Thirdly, household size has a negative impact on eight categories of consumption that bring indirect HCEs and the degree of impact in descending order is housing (−0.5131), food (−0.2231), transportation and communication (−0.1982), education and entertainment (−0.1107), clothing (−0.0967), daily necessities (−00643), other categories (−0.0789), and medical care (−0.0092). The upgrading of household consumption structure and the miniaturization of household size promote the increase HCEs. These carbon emission reduction potentials from different spending categories highlight the importance of optimizing household consumption structure for carbon emission reduction in Chinese households.

Based on the above research results, the following policy implications can be drawn.

Firstly, it is necessary to optimize family structures and encourage economy sharing within families. The current society is facing aging populations, declining birth rates, and the emergence of concepts such as non-marriage and Dink families, which have led to the decline of average family size in China. The government should strive to optimize family structures and improve the coverage of social welfare to mitigate the trend of shrinking family sizes. For example, the government could alleviate social pressures through balancing regional housing prices and employment opportunities and reduce the phenomenon of young people's late or refusing marrying. Given the positive role of the elderly in family carbon reduction, the government should guide young people, especially urban youth, to live together with their aging parents. In addition, the entire society should provide more convenience and support for young people to cohabit with the elderly. This not only reduces the number of families and *per capita* living space but also helps the elderly use more energy-efficient household appliances, promoting carbon emission reduction and maximizing the scale economy, while encouraging the sharing of goods and services between families to promote the sharing economy within household.

Secondly, it is necessary to optimize the family consumption structure and advocate for a low-carbon consumption approach. The government should consciously establish a green consumption policy system to promote a low-carbon and environmentally friendly lifestyle. For example, using low-carbon labels can inform consumers about the carbon content of products and services, influencing their purchasing decisions. Considering that family consumption decisions are affected by costs and prices, it is advisable to guide family consumption behavior through measurements such as fuel taxes, congestion charges, carbon taxes on high-carbon products, and tiered electricity pricing. Establishing a personal carbon account is also beneficial to create a personal carbon tax system, which can digitally record an individual's carbon emissions in clothing, food, housing, and transportation. Additionally. guiding small-scale families to choose green, low-carbon products plays an important role through incentive mechanisms, such as green buildings, green food, and new energy vehicles, encouraging the use of public transportation, promoting environmentally friendly shopping, or low-carbon consumption packaging, etc. Encouraging enterprises to

provide more intensive residential apartments, low-power appliances, and miniaturized daily necessities suitable for small-scale families is also a step forward. The housing sector has become a sector with great potential for reducing carbon emissions (Dusan Gordic, 2023), and the government could design balanced rental and purchase schemes to allow renters to enjoy the same public rights as homeowners, increasing the consumption nature of housing and reducing its investment nature (Zhao et al., 2023).

Thirdly, it is necessary to tap into the potential of rural HCEs. Strengthen the transformation of traditional energy in rural areas, for example, by implementing policies to change from coal to gas, which greatly reducing the proportion of rural direct carbon emissions. Meanwhile, enhancing the education and publicity of energy-saving and emission-reduction contributes to raising the awareness of energy conservation and emission reduction among rural families.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

HS: Conceptualization, Formal Analysis, Supervision, Writing–original draft, Writing–review and editing. MY: Data curation, Formal Analysis, Writing–original draft. MX: Formal Analysis, Software, Validation, Writing–review and editing. DY: Data curation, Software, Visualization, Writing–review and editing. FG: Conceptualization, Supervision, Writing–original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Sustainable growth unveiled: exploring the nexus of green finance and high-quality economic development in China

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Amidst global sustainability challenges, green finance emerges as a crucial instrument for advancing sustainable development, garnering increasing attention for its pivotal role in fostering high-quality economic development (HQED), particularly within the dynamic economic landscape of China. This study delves into the nexus between green finance and HQED across 30 Chinese provinces from 2012 to 2021. Employing the entropy method, indices for green finance and HQED index system are calculated, and their interaction is analyzed through a panel data model, incorporating tests for moderating effects of FinTech and green technological innovation, as well as assessing the heterogeneity across diverse regions. The findings highlight green finance's significant role in enhancing HQED, with notable regional disparities. Specifically, the eastern region shows the strongest impact, followed by the central region, while the western and northeastern regions exhibit weaker influences. The study also identifies FinTech and green technological innovation as pivotal moderators, amplifying green finance's positive effect on HQED. These insights underscore green finance's importance in driving sustainable economic growth and highlight the necessity for region-specific strategies to optimize its impact. Policy recommendations based on these findings include prioritizing the development of green finance, formulating region-specific strategies, and leveraging the catalytic roles of FinTech and green technological innovation to enhance the efficacy of green finance in achieving HQED.

KEYWORDS

green finance, high-quality economic development (HQED), FinTech, green technological innovation, regional disparities

1 Introduction

In recent decades, the pursuit of economic growth worldwide has often come at a significant environmental cost, including rampant natural resource consumption, energy overuse, and escalating carbon emissions. These practices have led to environmental degradation, climate change, and increased economic vulnerability, posing formidable challenges to sustainable development (Tol, 2009; Hafeez et al., 2019; Islam et al., 2022). Recognizing these challenges, the United Nations introduced the "2030 Agenda for Sustainable Development", setting a global direction towards reconciling economic growth with environmental conservation. Amidst this global context, as one of the largest developing countries in the world, China's journey of remarkable economic expansion has unfolded, marked by a GDP increase from 367.87 billion yuan in

1978 to 121,020.72 billion yuan in2022[1]. However, this growth has been accompanied by substantial environmental and social costs, including excessive resource consumption, severe pollution, and widening inequalities (Gao et al., 2022; Wang et al., 2023).

In addressing these challenges, China's economic development strategy is undergoing a fundamental shift. The previous model, focused solely on GDP growth, is gradually transitioning to a balanced and sustainable approach, emphasizing the quality of economic development (Yang, 2023). This strategic pivot underscores the essential link between China's development path and broader sustainability challenges, highlighting the country's commitment to playing a responsible role in global environmental governance.

To achieve a balanced and sustainable model of economic development, the Chinese government has prioritized high-quality economic development (HQED) as the paramount endeavor in building a comprehensively modernized nation. This strategy emphasizes a novel development concept, asserting that success should not be measured solely by GDP growth rates. High-quality development must be driven by innovation as the primary force, characterized by coordination as an intrinsic feature, manifested through a green and sustainable approach, pursued through openness as an essential pathway, and aimed at achieving shared prosperity as the fundamental goal.

Against this backdrop, green finance, as a crucial component supporting green development, integrates environmental protection into financial activities, utilizing financial tools and policies to facilitate the transformation and enhancement of businesses (Khan et al., 2022a). Green finance occupies a central role in transitioning economic development towards pathways that are green, low-carbon, and circular (Fu et al., 2023; Kumar et al., 2023), positioning as an indispensable driver of HQED.

However, green finance may also pose numerous challenges to socioeconomic development. Firstly, the redirection of funds from traditional industries to more environmentally friendly projects through green finance increases the financial burden on polluting industries. This necessitates greater expenditure by these industries to adopt cleaner technologies or even exit the market (Xiong et al., 2023). Secondly, the advancement of green finance within China is currently hindered by issues such as a monolithic structure, incomplete information disclosure, low returns, long investment horizons, and significant risks. These factors render current green finance initiatives less conducive to long-term sustainable development (Chen et al., 2023). Thirdly, the transition of developing economies to green finance faces high financial challenges, implying that green finance also introduces transitional risks (OECD, 2016). Therefore, researching the factors and relationships impacting green finance and HQED, and promoting their coordinated advancement, is a topic of widespread interest and urgent inquiry among academics and governments at all levels. This research direction holds significant theoretical and practical implications for guiding policy formulation in China, optimizing economic structures, and advancing local sustainable development.

Furthermore, Financial technology (FinTech), emerging from the profound integration of modern information technology and traditional financial services, started relatively late in China but has undergone rapid development (Wu, 2018), serving as a pivotal catalyst for economic growth. FinTech effectively tackles challenges in customer acquisition and risk management by leveraging advanced technologies such as blockchain, big data, cloud computing, and artificial intelligence. This advancement significantly expands the scale and efficiency of financial supply, thereby laying a solid foundation for HQED. Simultaneously, green technological innovation focuses on mitigating pollution, enhancing the efficiency of technological progress, and promoting the concurrent advancement of ecological environmental protection and socioeconomic development (Lv et al., 2021). It reduces high consumption and pollution through green technologies, alleviating resource pressure, improving the ecological environment, and enhancing corporate competitiveness. This, in turn, increases the efficiency of economic operations and elevates HQED.

Academics have undertaken extensive investigations into the factors influencing HQED from various perspectives, including green finance, FinTech and green technological innovation, which provides a solid reference base for this research. Nonetheless, there remains a noticeable void in the literature regarding a comprehensive framework that integrates these elements. To bridge this gap, this paper employs panel data from 30 Chinese provinces covering the period from 2012 to 2021. Under the new development concept, this study constructs a HQED index system incorporating five dimensions: innovation, coordination, green, openness, and sharing. Additionally, it establishes a green finance index system comprising green credit, green securities, green investment, green insurance, and carbon finance. By utilizing panel data models, the study empirically analyzes the impact relationship between green finance and HQED across Chinese regions from the perspectives of FinTech and green technological innovation and conducts an analysis of regional heterogeneity. The aim is to provide region-specific strategies for local government and market practices, contribute to the realization of a sustainable development model for China, and thus promote economic development towards a more green, efficient, and balanced direction.

The remainder of this study is organized in the following manner: the second section provides a review of the extant literature; the third section articulates the theoretical framework and posits research hypotheses; the fourth part discusses the model construction and variable measurement. The fifth section presents an analysis of the empirical findings, including tests of mechanisms, robustness checks, and examinations of heterogeneity. The concluding section outlines the study's findings, offers policy implications, acknowledges the research's limitations, and suggests avenues for future inquiry.

2 Literature review

Green finance, as a novel financial paradigm, sets itself apart from traditional finance by leveraging diverse financial instruments and products to address environmental pollution risks, aiming for green development (Khan et al., 2022b). Unlike conventional finance, green finance is committed to promoting environmental

1 Data source: "China Statistical Yearbook".

betterment and achieving economic sustainability (Yin and Xu, 2022). Early research in the field of green finance predominantly focused on micro-level analyses, such as investigating the roles that financial institutions play in environmental preservation and the promotion of sustainable economic growth (White, 1996; Jeucken and Bouma, 2017). Recently, the academic community has shifted its focus towards the interplay between green finance and corporate performance, with many scholars advocating a positive correlation between the two. Xu et al. (2020), using a meta-analytic approach, discovered a substantial positive link between green finance and corporate green performance. Lu et al. (2022), based on publicly listed companies in the A-share market and utilizing the Difference-in-Differences (DID) method, concluded that green finance significantly bolsters firms' capacity for green technological innovation by reallocating internal and external financing constraints. Du et al. (2022), also utilizing the DID approach, examined the motivational effects of the Green Credit Guidelines (GCG) on the technological innovation and financial performance of China's listed green companies, finding that green finance actively stimulates technological innovation and financial performance in these enterprises. Wang et al. (2022) using data from listed companies in China, assessed the influence of green finance on corporate ESG performance, observing an overall enhancement in corporate ESG due to green finance policies, with the effects varying across different governance structures. Yu et al. (2023) have developed a regional green finance development index in order to evaluate the influence of green finance on the financial performance of green enterprises within the context of China. Their findings indicate that green finance effectively enhances the financial performance of these enterprises, primarily through the mechanisms of capital concentration and information dissemination. Sun et al. (2023) applied the DID model to examine the effects of green finance policies on firms' ESG performance, showing a positive effect on ESG outcomes. Berikhanovna et al. (2023) utilized a panel regression model to investigate the Green Credit Policy (GCP)'s effect on firms' green innovation, transformation, and upgrading. Their findings indicate a positive and statistically significant effect, particularly within the context of large firms.

The concept of high-quality development is characterized by efficient, equitable, and green sustainable growth, aimed at fulfilling the increasingly sophisticated aspirations of the populace for a better life. It involves the harmonious progress of five key areas: economic development, political stability, cultural enrichment, social progress, and ecological civilization (Zhang et al., 2019). In the study of HQED, the academic community commonly employs Green Total Factor Productivity (GTFP) as a metric to assess the quality of economic development. Most studies use Data Envelopment Analysis (DEA) to calculate GTFP, explaining the level of HQED, as DEA circumvents the need for a specified production function and accommodates multiple inputs and outputs, making the measurement of HQED more convenient and comprehensive (Yu et al., 2019). Mei and Chen (2016) integrated DEA with the Directional Distance Function, utilizing the BML index to gauge China's TFP under constraints of carbon emissions and energy input, thus depicting the economic growth quality. Yu et al. (2019) calculated the GTFP of 230 cities as a vital gauge of high-quality development using the SBM model that includes undesirable outputs, examining the spatial-temporal dynamics of China's economic transition from a phase of rapid growth to one characterized by high-quality development, spanning the period from 2003 to 2016. Li, (2023) employed the U-SE-SBM-DEA model, along with the global reference ML index to assess the inclusive GTFP. They posited that inclusive green TFP can embody a new development pattern centered on the domestic grand cycle, scientifically encompassing innovation, coordination, green, and sharing concepts, effectively reflecting the level of HQED in China. Zhang et al. (2021) identified green productivity as an indicator of HQED, observing that green finance boosts green productivity by reducing pollution emissions and enhancing clean production, thus advancing HQED. Liu et al. (2023) argued that the quality in HQED not only pertains to utility but also to cost-effectiveness, quality expectations, and competitiveness. Consequently, a steady increase in TFP is considered a key indicator of HQED. Dongming et al. (2023) used the Global Malmquist-Luenberger (GML) productivity index, with inputs including capital stock, labor, and energy consumption, desired output as GDP, and undesirable outputs as emissions of sulfur dioxide, wastewater, and smoke dust, to measure HQED. However, traditional TFP, focusing solely on input constraints of production factors like labor and capital, fails to account for environmental pollution and resource impacts, thus inadequately reflecting the economic effects and resource allocation of production factors, and cannot accurately measure the economic development levels (Hua et al., 2021).

In the realm of green finance and its relationship with sustainable economic development, early theories on green finance predominantly emphasized the critical role of banks and other financial entities in environmental conservation and the promotion of economic health (Jeucken, 2010; Scholtens, 2017; Eremia and Stancu, 2006). Additionally, scholars have also explored the impact of green finance on both the economy and the environment from a macroeconomic perspective. For instance, Salazar (1998) argued that green finance effectively bridges the environment with the economy, enabling economic growth while considering environmental protection. Climent and Soriano (2011) discovered that the innovation and deployment of green financial tools, including green funds, green credits, green bonds, and green insurance, can significantly stimulate economic development and enhance its vitality. Recent studies have leaned more towards examining the relationship between green finance and sustainable economic growth. Pradhan et al. (2018), after analyzing the interconnections between energy consumption, financial development, and economic growth in Financial Action Task Force (FATF) countries, suggested that governments should endorse investments in green finance, particularly within clean energy sectors like natural gas, which not only aid in environmental protection but also foster economic growth. Sachs et al. (2019) noted that innovative financial instruments and policy measures, including green bonds, green banks, carbon market tools, fiscal policies, and green central banking, have opened new avenues for green projects, aiding in achieving sustainable development goals. He et al. (2019) observed that investments in renewable resources have a dual threshold effect on green economic development, indicating that, over the long haul, green investments in renewable energy are capable of driving green

economic growth effectively. Moreover, Wang et al. (2022) evaluated the causal dynamics between green finance and sustainable development on a global level using the bootstrap rolling-window Granger causality test. Their empirical findings indicate that green finance has positive effects on sustainable development across various subperiods. Mohsin et al. (2023), through empirical research, also identified green finance as a key element in green and sustainable development. Boubaker and Le (2024) noted that green finance is crucial in fostering sustainable development by steering financial resources towards environmentally sustainable projects. In summary, the aforementioned studies primarily investigate from the perspective of green or sustainable economic development, overlooking a more comprehensive assessment of the quality of economic development.

However, current research on the relationship between green finance and HQED predominantly focuses on the measurement of development levels, with most analyses grounded in theoretical exploration and less in empirical studies. A review of existing literature reveals that numerous scholars have investigated the role of green finance and its impact on HQED, with the majority indicating that green finance can foster such development. Despite rich theoretical analyses enhancing our understanding of this field, the lack of sufficient empirical testing means these conclusions require further validation. To address this gap, this paper employs a combined theoretical and empirical approach, aiming to delve deeper into the exact impact of green finance on HQED, thereby enhancing the credibility of the research.

Compared to existing research, this paper potentially offers innovations in the following three aspects: Firstly, it constructs a multidimensional perspective for measuring HQED. Most scholars, while studying the nexus between green finance and economic growth, have used GDP as the economic growth indicator, this approach fails to fully capture how green finance influences the quality of economic growth. This paper, however, develops HQED indicators from five aspects: innovation, coordination, green, openness, and sharing. It focuses not only on the speed of economic growth but also emphasizes its sustainability, balance, and comprehensiveness, aligning with the call of the national development policy in the new era. Secondly, the paper introduces the mechanistic roles of FinTech and green technological innovation. These two mechanism variables provide a new perspective to understand the pathways of green finance's impact, aiding in the exploration of factors influencing HQED through green finance. Thirdly, the paper's heterogeneity analysis involves a division into four regions. Following the economic regional classification method released by China's National Bureau of Statistics in 2011, which categorizes China into four main regions. This classification, based on socioeconomic characteristics including levels of economic development, industrial structure, and resource endowment, is more suitable for our research subject. This assists in revealing the heterogeneity in green finance development and HQED across different regions, providing a basis for formulating more targeted regional policies.

Building on these innovations, this study firstly examines the impact relationship between green finance and HQED, aiming to enrich the body of research on the determinants of HQED. Secondly, it investigates the moderating effect of green finance on HQED from the perspectives of FinTech and green technological innovation, thereby broadening the scope of external mechanism research between green finance and HQED. Finally, drawing on the insights garnered from this study, the paper offers policy recommendations for governments to enhance the green finance policy system and achieve HQED.

3 Theoretical analysis and research hypothesis

China's economy has undergone a pivotal transformation, shifting from a period characterized by swift expansion to a stage of high-quality development. In this new phase, green development has become crucial. It is not only integral to HQED but also a vital pathway for transitioning from traditional economic growth models to high-quality development. Green finance, through activities such as green credits, green securities, green investments, and green insurance, directs social capital into environmentally friendly industries, energy-saving industries, renewable energy, and clean transportation. At the same time, it reduces financial support for high pollution levels, excessive energy consumption, and significant emissions sectors. This approach lowers the investment and financing costs for green sectors, reshapes industrial and energy structures, and further propels HQED. Green finance not only alters corporate production methods but also significantly impacts consumer behavior and habits. It guides consumers towards more environmentally-friendly consumption patterns, fostering the rise of green consumption. Particularly in the area of green credits, methods like lowering loan interest rates and increasing credit limits can incentivize the acquisition of eco-friendly products, like new energy vehicles, thereby reducing pollution emissions and promoting the consumption of energy-saving and environmentally friendly products. This consumer behavior stimulates demand for environmentally friendly and green products, prompting the production side to increase the supply of these products and create more employment opportunities. Concurrently, as production scales up, it reduces the prices of consumer goods, further encouraging consumption and creating a virtuous cycle that robustly drives HQED. In light of the foregoing discussion, this paper introduces Research Hypothesis 1:

H1. Green finance significantly promotes HQED.

Technological innovation, particularly green technological innovation, serves as a vital driver of economic growth and a crucial factor in achieving HQED. The process of technological innovation requires substantial investment in research and development (R&D), especially for small and medium-sized enterprises (SMEs), for whom acquiring market financing is a key channel for technological innovation. Green finance facilitates this by providing credit support to green enterprises and issuing green bonds, thereby alleviating the financial burden of R&D and spurring technological innovation, which in turn fosters green and innovative development in the economy. For enterprises characterized by high pollution levels, excessive energy consumption, and significant emissions, green finance promotes technological innovation by guiding capital outflows and restricting credit through financial measures. This compels these enterprises to

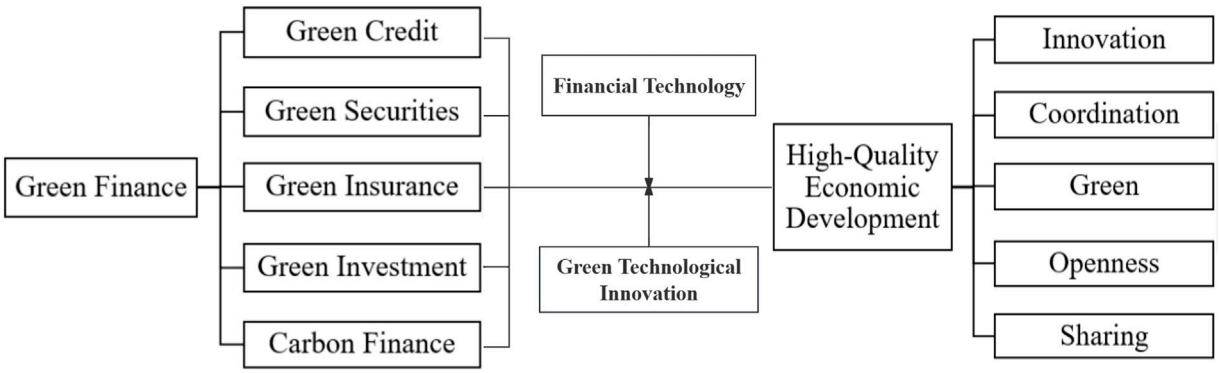


FIGURE 1
Mechanisms of green finance impact on HQED.

innovate, aiming to achieve energy efficiency, emission reduction, and HQED. The higher the level of investment in technological R&D, the more green finance can stimulate innovative output, enhancing its role in promoting HQED. In view of the analysis presented above, this paper posits Research Hypothesis 2:

H2. Green technological innovation positively moderates the effect of green finance on HQED.

Financial technology (FinTech), as a product of the deep integration between modern information technology and traditional financial services, started relatively late in China but has shown rapid development (Wu, 2018). It has demonstrated tremendous potential in enhancing the efficiency of financial services and propelling the real economy forward. On one hand, FinTech facilitates faster and more accurate information transmission among various parties in financial activities, significantly reducing information asymmetry. On the other hand, the efficiency of FinTech enables better fulfillment of enterprises' innovative financing needs, creating a favorable financial ecosystem[2] for sustainable corporate development. The objective of green finance is to foster the advancement of green industries, thereby aiding HQED. Given the characteristics of green industries, where green innovation projects typically involve high initial investment and significant uncertainty, and considering that China's economy is transitioning from rapid expansion to high-quality advancement, replacing old drivers with new ones, the development of green industries has yet to reach maturity. FinTech can aid financial institutions in better identifying green innovation enterprises with potential and strength by reducing information asymmetry. It can provide these projects and businesses with more transparent, friendly, green, efficient, and automated financial support. As increasing financial support and resources flow towards sustainable green fields, green industries will gradually achieve scale effects. In this context, FinTech plays a crucial role in bridging this financial gap, ultimately facilitating the efficient transformation of China's economic development and promoting high-quality growth. Accordingly, the paper proposes Research Hypothesis 3:

H3. FinTech positively moderates the effect of green finance on HQED.

In summary, the mechanism of green finance's effect on HQED is shown in Figure 1.

4 Model construction and variable measurement

4.1 Data sources

This paper seeks to investigate the nexus between green finance and HQED across 30 provinces in China (Tibet, Hong Kong, Macau, and Taiwan excluded) over the period from 2012 to 2021. The data sources include various annual statistical year-books such as the "China Statistical Yearbook," "China Science and Technology Statistical Yearbook," "China Environment Statistical Yearbook," "China Energy Statistical Yearbook," "China Industrial Statistics Yearbook," "China Insurance Statistical Year-book," "China Economic Census Yearbook," and "China Energy Statistics Yearbook." In addition, provincial statistical yearbooks and a series of databases like the economy prediction system (EPS), CSMAR (China Stock Market & Accounting Research Database), Wind, and environmental bulletins are also utilized. For the few instances of missing data, interpolation methods were applied to estimate missing values.

4.2 Variable selection and measurement

4.2.1 Explained variable: high-quality economic development

HQED research is primarily categorized into two types: the first utilizes Total Factor Productivity (TFP) as a metric to evaluate economic growth quality (Mei and Chen, 2016; Zhang et al., 2023); the other, deriving from the new development concept, devises a comprehensive evaluation system with multiple indicators for HQED (Zhou et al., 2022). Conventional TFP measures focus

2 Financial ecosystem refers to the infrastructure, fundamental institutions, and external economic environment on which financial operations rely (Xu, 2005).

solely on input limitations of production factors such as labor and capital, neglecting the impact of environmental pollution and resource use, thus failing to comprehensively reflect the economic effects and resource allocation status of production factors, thereby inaccurately measuring the level of economic development (Hua et al., 2021). This study, predicated on an in-depth analysis of the connotations of HQED, in conjunction with the availability of data and referencing the research methodology of Sun et al. (2020), Chen and Huo (2022) and Mao et al. (2023), constructs an index system under the new development concept. This system encompasses five dimensions—innovation, coordination, green, openness, and sharing, comprising five secondary indicators and 26 tertiary indicators. The entropy method is employed to calculate the HQED level across Chinese provinces, with the specific indicators enumerated in Table 1.

Based on the aforementioned methodologies, we computed the HQED indices for the 30 provinces in China in 2012, 2017, and 2021. It is evident from Figure 2 that China's HQED level displays significant regional heterogeneity. Beijing, Tianjin, and Shanghai consistently exhibit markedly higher HQED levels compared to other provinces throughout the entire period. This phenomenon can be attributed to the policy support enjoyed by municipalities directly under the central government, affording them the ability to consolidate various advantageous resources and thereby gain an absolute advantage in HQED. Conversely, western regions, notably the northwest, consistently manifest lower levels of HQED relative to their counterparts, which can be ascribed to factors such as restricted resource accessibility, underdeveloped infrastructure, and a less conducive policy environment compared to the eastern coastal provinces. Specifically, in 2012, coastal provinces in the eastern region generally outpaced inland provinces in terms of HQED. However, by 2017, after 5 years of development, central regions, particularly provinces surrounding Hubei province, witnessed significant improvements in HQED. In 2021, there was a notable further enhancement in HQED observed in both central and western regions of China, albeit the enduring pattern of higher HQED levels in the east and lower levels in the west persisted. These regional disparities in HQED can be attributed to various factors, including disparities in economic structure, resource endowment, level of industrialization, infrastructure development, and policy support.

4.2.2 Core explanatory variable: green finance

Green finance in China is a multifaceted concept, and this study aims to develop a comprehensive green finance index by considering its main components. Leveraging available data and inspired by the research methodologies of He et al. (2019) and Xu et al. (2023), the green finance index is developed encompassing five principal aspects: green credit, green securities, green investment, green insurance, and carbon finance. Firstly, due to the absence of provincial-level statistics on China's green credit balance, we employ the interest expense ratio of enterprises in the six major high-energy-consuming industries to their total expenses and the Credit Proportion of Environmental Protection Projects as proxies for assessing green credit; Secondly, green securities demonstrate the financial endorsement of the capital market towards energy-saving and environmental protection enterprises. Owing to the late start of green securities and the difficulty in obtaining provincial-level data, this dimension is evaluated based on the market value ratio between listed companies operating in environmental protection sectors and those engaged in the six major high-energy-consuming industries; Thirdly, internationally recognized green insurance primarily encompasses environmental pollution liability insurance and catastrophic disaster insurance. In China, the implementation of compulsory environmental pollution liability insurance only commenced in 2013, resulting in a limited time frame and lacking systematic statistical data. Thus, the development of agricultural insurance, which is significantly affected by natural conditions, is selected as a measure; Fourthly, green investment is represented by the proportion of investment allocated to environmental pollution control and public expenditure on energy-saving and environmental protection; Lastly, carbon finance is denoted by the ratio of domestic and foreign currency loans to carbon emissions. The specific indicators are detailed in Table 2.

4.2.3 Moderating variables

The development status of FinTech can be indirectly gauged through the search indices of related keywords. This study utilized the Baidu search index to gather data on the number of searches for FinTech-related keywords in various Chinese provinces from 2012 to 2021, subsequently constructing a FinTech development index. This index reflects the prevalence of FinTech across different regions and time points, meeting the provincial panel data requirements of this research. In determining the keywords, this study initially referred to existing academic research (Yue and Pin, 2015; Sheng and Fan, 2020). Considering the data availability from Baidu search index, a list of keywords related to FinTech was selected for the study. These keywords reflect the diverse applications of FinTech from different perspectives: firstly, from the basic technology perspective, including "big data," "cloud computing," "artificial intelligence," "blockchain," "biometrics,"; secondly, from the funds payment perspective, covering "online payment," "mobile payment," "third-party payment,"; thirdly, FinTech intermediary service models, involving "online lending," "online financing," "internet financing," "internet micro-loans," "internet loans," "internet banking," "electronic banking," "online banking," "open banking," "internet banks," "direct banks,"; and fourthly, direct terms related to FinTech, such as "internet finance," "FinTech." In terms of data processing, the study employed the entropy method to determine the weights of the aforementioned keywords in each dimension, thereby integrating multiple in-dices into a single comprehensive index. This method not only ensures the scientific and objective nature of the composite index but also effectively reveals the comprehensive development level of FinTech in various aspects. The specific indicators are detailed in Table 3.

Green technological innovation is crucial in driving economic growth and sustainable development. Patents are recognized as a standard measure of a company's technological innovation capacity by the academic community and reflect an enterprise's capability to innovate in new processes, materials, and technologies (Semenova

TABLE 1 Index system for HQED.

Level 1 indicator	Level 2 indicator	Level 3 indicator	Indicator definition	Indicator direction	References
High-quality economic development	Innovation	GDP Growth Rate	(Current Period GDP - Previous Period GDP)/Previous Period GDP	+	Sun et al. (2020)
		R&D Investment Intensity	R&D Spending of Industrial Enterprises above a Designated Size/GDP	+	Sun et al. (2020)
		Investment Efficiency	Investment Rate/Regional GDP Growth Rate	-	Sun et al. (2020)
		Innovation Level	Logarithm of the Number of Patent Applications for Inventions	+	Chen and Huo (2022)
		Technology Market Development Level	Technology Transaction Volume/GDP	+	Sun et al. (2020)
	Coordination	Social Consumption Level	Total Retail Sales of Consumer Goods/GDP	+	Sun et al. (2020)
		Urban-Rural Structure	Urban Population/Total Population	+	Sun et al. (2020)
		Government Debt Burden	Government Debt Balance/GDP	-	Sun et al. (2020)
		Advanced Industrial Structure	Output Value of Tertiary Industry/Secondary Industry	+	Mao et al. (2023)
		Urban-Rural Income Structure	Urban Residents Per Capita Disposable Income/Rural Residents Per Capita Disposable Income	-	Mao et al. (2023)
		Urban-Rural Consumption Structure	Urban Residents Per Capita Consumption/Rural Residents Per Capita Consumption	-	Mao et al. (2023)
	Green	Energy Consumption Elasticity Coefficient	Energy Consumption Growth Rate/GDP Growth Rate	-	Sun et al. (2020)
		Wastewater per Unit Output	Wastewater Discharge Volume/GDP	-	Sun et al. (2020)
		Waste Gas per Unit Output	Sulfur Dioxide Emission Volume/GDP	-	Sun et al. (2020)
		Greening Level in Built-up Areas	Green Covered Area/Total Built-up Area	+	Mao et al. (2023)
		Environmental Protection	Garbage Treated Harmlessly Volume/Garbage Produced Total Volume	+	Chen and Huo (2022)
	Openness	Foreign Trade Dependency	Total Import and Export Volume/GDP	+	Sun et al. (2020)
		Degree of Openness to the Outside World	Total Foreign Investment/GDP	+	Sun et al. (2020)
		Marketization Level	Regional Marketization Index	+	Sun et al. (2020)
	Sharing	Proportion of Labor Compensation	Labor Compensation/Regional GDP	+	Sun et al. (2020)
		Transportation Infrastructure Level	Logarithm of Highway Mileage	+	Mao et al. (2023)
		Theil Index	Per Capita Disposable Income Growth Rate/Regional GDP Growth Rate	-	Liu et al. (2023)

(Continued on following page)

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TABLE 1 (*Continued*) Index system for HQED.

Level 1 indicator	Level 2 indicator	Level 3 indicator	Indicator definition	Indicator direction	References
		Urban-Rural Consumption Gap	Per Capita Consumption Expenditure of Urban Residents/Per Capita Consumption Expenditure of Rural Residents	-	Sun et al. (2020)
		Medical and Health Level	Number of Health Technicians per 10,000 People	+	Chen and Huo (2022)
		Unemployment Situation	Urban Registered Unemployed Number/(Urban Registered Unemployed Number + Urban Registered Employed Number)	-	Chen and Huo (2022)
		Social Welfare	Per Capita Public Library Collection	+	Mao et al. (2023)

Note: The indicators are categorized into three levels. Level 1 Indicator represents the main category of high-quality economic development. Level 2 Indicator represents subcategories within the main category, and Level 3 Indicator represents specific metrics within each subcategory. Indicator Definition provides the calculation or explanation of the metric. Indicator Direction (+ or -) indicates whether an increase in the indicator is considered positive (+) or negative (−) for high-quality economic development.

et al., 2023). This paper, following the "International Patent Green Classification List" promulgated by the World Intellectual Property Organization (WIPO) in 2010, matches the number of green patents applied for and granted at the provincial level annually. Considering that patent grants require time and may impact the economy and society during the granting process, patent applications, as opposed to granted patents, are more timely and reliable. Therefore, drawing on the research of Wurlod and Noailly (2018) and Deng et al. (2021), this study adopts the tally of green invention patent applications as a measurement for green technological innovation.

4.2.4 Control variables

HQED is influenced not only by the advancement of green finance but also by other macroeconomic variables. Building upon the research of previous scholars and considering the current economic development landscape in China, this study controls a series of variables that affect HQED to mitigate biases caused by omitted variables. Specifically, it identifies a selection of macroeconomic variables as control factors: level of openness to the outside world (OPEN), human capital level (HUMAN), energy structure (ES), labor level (LABOUR), research and development intensity (R&D), and level of educational support (EDU).

The level OPEN reflects the degree of China's engagement with international markets, measured by the ratio of total imports and exports to the GDP. HUMAN is gauged by the proportion of higher education students to the total population, representing the country's educational level and talent resources. ES is indicated by the percentage of electricity consumption in total energy consumption, showcasing the structural characteristics of the nation in energy utilization. LABOUR is represented by the natural logarithm of the number of employed individuals, reflecting the scale and state of the labor market. R&D is evaluated by the ratio of R&D internal expenditures to GDP, assessing the nation's investment in scientific research and innovation. Lastly, EDU is denoted by the ratio of local fiscal education expenditure to general budget expenditure, reflecting the government's commitment to the education sector. By incorporating these variables, the study aims to comprehensively assess the influence of various macroeconomic factors on HQED. This approach enables a more nuanced understanding of how different economic elements interact and contribute to sustainable economic growth.

4.3 Empirical models and methods

4.3.1 Analytical method

This paper, referencing the research methodology of Zhang et al. (2023), employs the entropy method to measure the levels of green finance and HQED. This method uses the degree of variation among the values of various evaluation indicators to depict the importance of each indicator, thereby reducing biases caused by human factors to some extent. Before calculating the entropy value, to avoid subjective biases and address issues such as inconsistency in the types and dimensions of evaluation indicators, we first use the normalization method to dimensionlessly process the original indicators.

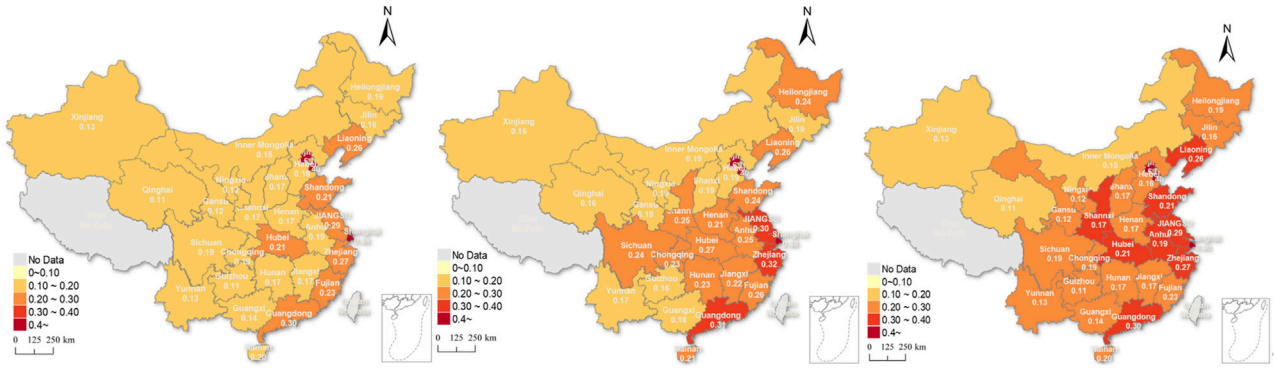


FIGURE 2
Spatial pattern of the HQED level in Chinese provinces in 2012, 2017, and 2021.

Data standardization process:

$$X_{ij} = \frac{x_{ij} - min\, x_{ij}}{max\, x_{ij} - min\, x_{ij}} \quad (1)$$

$$X_{ij} = \frac{max\, x_{ij} - x_{ij}}{max\, x_{ij} - min\, x_{ij}} \quad (2)$$

Eq. 1 standardizes positive indicators, while Eq. 2 standardizes negative indicators. Additionally, to eliminate the impact of zero and negative values, a minimum unit value θ is added to all standardized data results, making them suitable for calculation. Here, θ is set to 0.0001, resulting in X_{ij}'.

Calculation of indicator weights: The proportion of the i th option for the indicator, as shown in Eq. 3:

$$P_{ij} = \frac{X_{ij}'}{\sum_{i=1}^{n} X_{ij}'} \quad (3)$$

Calculation of indicator entropy: Using the results of Eq. 3 to calculate the information entropy D_j for the j th item:

$$D_j = -\frac{1}{\ln n}\sum_{i=1}^{n} P_{ij} \ln P_{ij} \quad (4)$$

Determination of indicator entropy redundancy: Employing the entropy value D_j from Eq. 4 to calculate the difference coefficient D_j for the jth item:

$$G_j = 1 - D_j \quad (5)$$

Calculation of weight results: Utilizing the results of Equation 5 to calculate the weight w_j of the indicator, as illustrated in Equation 6:

$$w_j = \frac{G_j}{\sum_{j=1}^{m} G_j} \quad (6)$$

Comprehensive development level index measurement: The comprehensive evaluation value is the sum of the products of each indicator's score and its weight, as shown in Equation 7:

$$U_j = \sum_{j=1}^{m} w_j \times X_{ij} \quad (7)$$

4.3.2 Panel regression model

In pursuit of exploring the effects of green finance on indicators of HQED, we referenced the research methodology of Balestra and Nerlove (1966). The ensuing regression model was formulated as follows:

$$HQED_{it} = \alpha_0 + \alpha_1 GF_{it} + \eta X_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (8)$$

in Eq. 8 $HQED_{it}$ denotes the dependent variable, representing the level of HQED in region i during year t; GF_{it} is the core explanatory variable, denoting the level of green finance in region i for year t. X_{it} refers to a set of control variables, which include the level of openness to the outside world (OPEN), human capital level (HUMAN), energy structure (ES), labor level (LABOUR), research and development intensity (R&D), and level of educational support (EDU). α_0 is the constant term, α_1 and η respectively represent the regression coefficients; ε_{it} represents the model's random disturbance term, encapsulating unobserved factors that may affect the dependent variable, while μ_i and δ_t denote individual fixed effects and time fixed effects, respectively.

4.3.3 Moderating effect model

In the process where green finance facilitates HQED, FinTech plays a pivotal moderating role. Consequently, this paper delves further into whether green finance promotes HQED through FinTech. Drawing on the methodologies of Frazier et al. (2004), an interaction term between green finance and FinTech is incorporated into the regression equation, leading to the construction of the following panel data model,

$$HQED_{it} = \alpha_0 + \alpha_1 GF_{it} + \alpha_2 GF_{it}{*}FT_{it} + \alpha_3 FT_{it} + \eta X_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (9)$$

in Eq. 9 FT_{it} denotes the FinTech, $GF_{it}{*}FT_{it}$ signifies the interaction terms between green finance and FinTech. Prior to calculating the multiplicative terms, independent variables and moderators were standardized to mitigate concerns of multicollinearity (Aiken and West, 1991).

Additionally, this paper will further examine whether green technology innovation amplifies the effect of green finance on HQED. To investigate this, the following panel data model is constructed,

$$HQED_{it} = \alpha_0 + \alpha_1 GF_{it} + \alpha_2 GF_{it}{*}GTI_{it} + \alpha_3 GTI_{it} + \eta X_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (10)$$

in Eq. 10 GTI_{it} denotes the green technological innovation level, $GF_{it}{*}GTI_{it}$ represents the interaction terms, which have also been standardized to minimize multicollinearity.

TABLE 2 Index system for Green Finance.

Level 1 indicator	Level 2 indicator	Level 3 indicator	Indicator definition	Indicator direction	References
Green Finance	Green Credit	Interest Expenditure Ratio of High Energy Consumption Industries	Interest expenses of Six Major High Energy Consumption Industries/Total Industrial Interest	-	He et al. (2019)
		Credit Proportion of Environmental Protection Projects	Total Credit Amount Allocated for Environmental Protection Projects within the Province/Total Credit Amount of the Province	+	Xu et al. (2023)
	Green Securities	Market Value Proportion of Environmental Protection Enterprises Listed in A-shares	Market Value of Environmental Protection Enterprises Listed in A-shares/Total Market Value of Enterprises Listed in A-shares	+	He et al. (2019)
		A-share Market Value Proportion of High Energy Consumption Enterprises Listed in A-shares	Market Value of High Energy Consumption Enterprises Listed in A-shares/Total Market Value of Enterprises Listed in A-shares	-	He et al. (2019)
	Green Insurance	Agricultural Insurance Scale Proportion	Agricultural Insurance Expenditure/Total Insurance Expenditure	+	He et al. (2019)
		Agricultural Insurance Payout Rate	Agricultural Insurance Expenditure/ Agricultural Insurance Income	+	He et al. (2019)
	Green Investment	Investment Proportion in Environmental Pollution Control	Investment in Environmental Pollution Control/GDP	+	He et al. (2019)
		Proportion of Fiscal Expenditure on Environmental Protection	Fiscal Expenditure on Energy Conservation and Environmental Protection Industry/Total Fiscal Expenditure	+	He et al. (2019)
	Carbon Finance	Carbon Emission Loan Intensity	Balance of Domestic and Foreign Currency Loans/Carbon Emission	+	Xu et al. (2023)

Note: Level 1 Indicator represents the main category of green finance. Level 2 Indicator represents subcategories within the main category, and Level 3 Indicator represents specific metrics within each subcategory. Indicator Definition provides the calculation or explanation of the metric. Indicator Direction (+ or -) indicates whether an increase in the indicator is considered positive (+) or negative (−) for green finance.

4.3.4 Marginal effects analysis

To further elucidate the moderating effects of FinTech and green technological innovation more comprehensively, and following the research methods of McCabe et al. (2018) and Zhang and Liu (2015), the marginal effects of green finance on HQED at different percentiles of both FinTech and green technological innovation are computed. The calculation process for the marginal effect of green finance on HQED at a given level of the moderating variable is as follows:

For FinTech:

$$\frac{\partial HQED_{it}}{\partial GF_{it}} = \alpha_1 + \alpha_2 FT_{it} \tag{11}$$

For green technological innovation:

$$\frac{\partial HQED_{it}}{\partial GF_{it}} = \alpha_1 + GTI_{it} \tag{12}$$

Eqs 11, 12 indicate how the marginal effect of green finance on HQED varies with the levels of FinTech and green technological innovation.

5 Empirical analysis and results

5.1 Descriptive statistics

The descriptive statistics for the variables selected in this research are presented in Table 4. Analysis of the results from Table 4 reveals significant variations within the sample for both the HQED index and the green finance index. The minimum value of the HQED index is 0.107, and its maximum is 0.651, reflecting a progressive increase over time in the quality of economic development. Similarly, the green finance index exhibits a minimum value of 0.078 and a maximum of 0.633, signifying a growing trend in green finance over time. The descriptive statistical outcomes for the other variables are within reasonable bounds and are not elaborated further here.

5.2 Benchmark regression analysis

Prior to estimating the described models empirically, an assessment of multicollinearity was conducted to examine the extent of variance inflation factor (VIF) among the variables, with detailed findings presented in Supplementary Appendix SA. Subsequently, due to the utilization of panel data, a Hausman test was performed on the benchmark regression model (1). The results indicate the rejection of the null hypothesis favoring the random effects model, indicating a preference for adopting a fixed effects model for the benchmark regression analysis. The direct impact of green finance development on the HQED of China is presented in the regression results, as depicted in Table 5.

The findings presented in Table 5 indicate that the regression coefficients for the primary explanatory variables are significantly positive when analyzed using both individual fixed effects and

TABLE 3 Index system for FinTech.

Level 1 indicator	Level 2 indicator	Level 3 indicator	References
FinTech	Basic Technology	Big Data	Sheng and Fan (2020)
		Cloud Computing	Sheng and Fan (2020)
		Artificial Intelligence	Sheng and Fan (2020)
		Blockchain	Sheng and Fan (2020)
		Biometrics	Sheng and Fan (2020)
	Funds Payment	Online Payment	Yue and Pin (2015)
		Mobile Payment	Yue and Pin (2015)
		Third-Party Payment	Yue and Pin (2015)
	FinTech Intermediary Service Models	Online Lending	Sheng and Fan (2020)
		Online Financing	Yue and Pin (2015)
		Internet Financing	Yue and Pin (2015)
		Internet Micro-Loans	Sheng and Fan (2020)
		Internet Loans	Yue and Pin (2015)
		Internet Banking	Yue and Pin (2015)
		Electronic Banking	Yue and Pin (2015)
		Online Banking	Yue and Pin (2015)
		Open Banking	Yue and Pin (2015)
		Internet Banks	Sheng and Fan (2020)
		Direct Banks	Sheng and Fan (2020)
	Direct FinTech Terms	Internet Finance	Sheng and Fan (2020)
		FinTech	Sheng and Fan (2020)

Note: The Level 1 Indicator represents the overall category of FinTech, Level 2 Indicator represents the subcategories within FinTech, and Level 3 Indicator provides specific areas within each subcategory.

individual time two-way fixed effects models. Specifically, in columns (1) and (2), the impact of green finance on HQED is positive, with the regression coefficient in column (2) being 0.1511, higher than 0.0972 in column (1), both reaching the significant level of 1%. The coefficient of 0.1511 in column (2) implies that a one-unit increase in green finance development corresponds to a 0.1511 unit increase in HQED. This supports the theoretical analysis that green finance fosters HQED and also validates the proposed hypothesis H1 of this study. This conclusion aligns with the perspective that green finance is instrumental in promoting HQED, as echoed in prior research by Yang et al. (2021) and Chen et al. (2023).

Delving deeper, accounting for the time-lag effect of green finance development on HQED, the core explanatory variable lagged by one period was incorporated into columns (3) and (4) for regression analysis. Column (3) uses an individual time two-way fixed effects model, while column (4) uses an individual fixed effects model. The results demonstrate that the coefficients for green finance lagged by one period are significantly positive in both models, being 0.1016 and 0.1683 respectively, and both achieving the significant 1% level. Compared to the non-lagged regression outcomes, these figures reveal higher coefficients and levels of significance, suggesting that green finance with a one-period lag exerts a more potent influence on HQED. This indicates a temporal delay in the impact of green finance development on HQED, meaning that the current level of HQED in a region is also affected by the green finance development of the previous period. This result aligns with the findings of a similar study conducted by Han et al. (2023). This delay can be attributed to the time required for the implementation and realization of benefits from certain green financial instruments.

In terms of control variables, the level of openness to foreign markets, human capital, and research and development intensity all showed a positive correlation with HQED. The significance of these factors highlights the crucial role of an open economy, a high-quality workforce, and sustained technological innovation in propelling HQED.

However, the negative correlation between labor force levels and high-quality development may suggest that merely increasing labor input is not effective in enhancing economic quality. This also implies that future economic growth is likely to rely more on improving labor productivity rather than on increasing the quantity of laborers. The negative coefficients of educational support, significant in columns (2) and (4), may indicate the delayed effects of education investment, which may not yield

TABLE 4 Descriptive statistics of the variables.

Variable	N	Mean	SD	MIN	P50	MAX
HQED	300	0.249	0.106	0.107	0.226	0.651
GF	300	0.186	0.082	0.078	0.163	0.633
GC	300	0.142	0.162	0.010	0.082	1.047
FT	300	0.216	0.159	0.005	0.179	0.842
GTI	300	0.404	0.543	0.004	0.199	3.227
OPEN	300	0.259	0.277	0.008	0.141	1.441
HUMAN	300	0.021	0.005	0.009	0.020	0.042
ES	300	0.033	0.023	0.004	0.026	0.095
LABOUR	300	7.606	0.766	5.624	7.674	8.864
R&D	300	0.017	0.012	0.004	0.015	0.065
EDU	300	0.185	0.032	0.106	0.185	0.262

Note: N denotes the number of observations; SD, denotes the standard deviation; MIN, P50, and MAX, denote the minimum, median (50th percentile), and maximum values of the variables, respectively.

immediate results in terms of HQED. Alternatively, this could be attributed to the increased education spending potentially crowding out investments in areas that have a more direct impact on HQED, such as technological innovation and environmental protection.

5.3 Endogeneity analysis

By incorporating a dynamic panel model to analyze the influence of green finance on HQED, and employing the System Generalized Method of Moments (System GMM) to estimate the dynamic panel within the panel, this study selects the first-order lag of the explained variable as an exogenous variable. This approach aims to address the issues of endogeneity and estimation bias present in static panel models. Specifically, in column (2), green finance lagged by one period is included as an independent variable for regression. The estimations derived from the System GMM model regarding the impact of green finance on HQED are illustrated in Table 6. Reflecting the dynamic panel model's nuances, the endogenous explanatory variables encompass green finance, level of openness to foreign markets, human capital, energy structure, labor level, and research and development intensity. To ensure the regression outcomes' integrity, evaluations for the model's validity and the instrumental variables' efficacy were conducted. The findings, as delineated in Table 6, reveal the error term's difference showcasing first-order autocorrelation without evidence of second-order autocorrelation, thus accepting the null hypothesis of no autocorrelation in the error term. The p-values for the Hansen test fall between 0.1 and 0.25, indicating that the regression results do not suffer from over-identification and that the number of instrumental variables is reasonable. As indicated in Table 6, green finance lagged by one period is significantly positive at the 5% level, demonstrating a positive effect of the previous period green finance on ensuing HQED, thereby verifying the temporal delay impact of green finance., thus confirming the time-lag effect of green finance. The influence coefficient of green finance on HQED is significantly positive at the 5% level, suggesting that green finance plays a positive guiding and promotional role in HQED. This research finding is consistent with the conclusion of the study by Li (2023), which used the GMM model to discover the promoting effect of green finance on HQED.

5.4 Analysis of moderating effects

Building upon the examination of green finance's impact on HQED, this study further incorporates variables of FinTech (FT) and green technological innovation (GTI) and constructs interaction terms to scrutinize the moderating effects of FinTech and green technology on green finance's role in enhancing HQED. Within the framework of the fixed effects model, a multivariate regression analysis is conducted using panel data. To empirically test the moderation effect model and address the issue of multicollinearity, the interaction terms in models (2) and (3) are decentered, with the regression results presented in Table 7. Column (1) demonstrates that green finance (GF) has a significant positive impact on HQED. Column (2) adds FinTech (FT) and the interaction term of green finance and FinTech (GF*FT) to column (1). It reveals that the interaction term's coefficient is significantly positive at the 1% level, underscoring that FinTech significantly enhances the positive effect of green finance on HQED, thus confirming the proposed hypothesis H3. This result aligns with the findings of a similar study conducted by Yang et al. (2021). It also further demonstrates that FinTech plays a moderating role in the impact of green finance on HQED. This may be attributed to FinTech improving the efficiency of financial services, thereby strengthening the role of green finance in resource allocation.

Column (3) examines the role of green technology innovation (GTI), with results indicating that the independent variable of green technology innovation has no significant impact on HQED. Column (4) incorporates the interaction term of green finance and green technology (GF*GTI), with its coefficient also being significantly

TABLE 5 Regression results of the impact of green finance on HQED.

	(1)	(2)	(3)	(4)
	HQED	HQED	HQED	HQED
GF	0.0972***	0.1511***		
	(3.3604)	(4.0338)		
GF_{-1}			0.1082***	0.1688***
			(3.5597)	(4.2710)
OPEN	0.0878**	0.0465	0.0948***	0.0481*
	(2.5496)	(1.5991)	(2.8967)	(1.8090)
HUMAN	0.7562	4.7709***	0.8604	4.6448***
	(0.5536)	(5.7201)	(0.6998)	(6.1760)
ES	0.3438	0.9167*	0.4791	0.9560*
	(0.7367)	(1.7862)	(1.1597)	(1.8619)
LABOUR	−0.0216	−0.0222	−0.0185	−0.0254
	(−0.8514)	(−1.1276)	(−0.7431)	(−1.3393)
R&D	3.0078***	5.6549***	3.0926***	5.3683***
	(2.8090)	(6.5438)	(2.9129)	(6.3614)
EDU	−0.0202	−0.3318**	−0.0429	−0.2579*
	(−0.1997)	(−2.7427)	(−0.3905)	(−1.9477)
Regional fixed effect	YES	YES	YES	YES
Time fixed effect	YES	NO	YES	NO
_cons	0.2666	0.2114	0.2445	0.2267
	(1.4075)	(1.3678)	(1.3240)	(1.5441)
N	300	300	270	270
adj.R^2	0.864	0.811	0.858	0.805

Note: *,** and *** indicate significance at the levels of 10%, 5%, and 1%, respectively. The values in brackets are t-statistics.

positive at the 1% level. This suggests that with the support of green finance, the application of green technology significantly positively contributes to HQED, confirming hypothesis H2. This conclusion is in harmony with the perspective that green technology serves as a moderator in the nexus between green finance and HQED, as suggested by Li (2023). These estimated outcomes posit that GTI constitutes a crucial conduit by which green finance bolsters HQED, indeed playing a positive moderating role. The rationale is that green finance can provide substantial funding for the development of GTI. With robust financial support, GTI more effectively serves industrial transformation, green development, innovative development, open development, inclusive development, thereby driving HQED.

To further elucidate the moderating effects of FinTech and GTI, we calculated the marginal effects. According to Table 7, the coefficient for the interaction term between green finance and FinTech is 0.2622, and the coefficient for green finance is 0.0743. Given the median (P50) value for FinTech is 0.179 (Table 4), using our formula (11), the marginal effect of green finance at P50 for FinTech is calculated as 0.0743 + 0.2622 × 0.179. Thus, at the 50th percentile of FinTech, the marginal effect of green finance on HQED is 0.1212. Similarly, for GTI, the coefficient for the interaction term between green finance and GTI is 0.0718, and the coefficient for green finance is 0.0800. Given the 50th percentile (P50) value for GTI is 0.1994, according to formula (12), the marginal effect of green finance at P50 for GTI is calculated as 0.0800 + 0.0718 × 0.1994. Thus, at the 50th percentile of GTI, the marginal effect of green finance on HQED is 0.0943.

Furthermore, we calculated the marginal effects at the 0th, 10th, 20th, ., and 100th percentiles of both FinTech and GTI, as displayed in Supplementary Appendix SB1. Specifically, at the 0th percentile of FinTech (i.e., the minimum value), the marginal effect of green finance on HQED is 0.0757. As FinTech advances to the 10th percentile, this marginal effect increases to 0.0870, demonstrating the enhancing role of FinTech in magnifying the impact of green finance. This trend continues, with the marginal effect reaching 0.2951 at the 100th percentile (the maximum value), which is approximately four times the initial value at the 0th percentile (the

TABLE 6 Endogeneity test regression results.

	(1)	(2)
	HQED	HQED
L.HQED	0.8857***	0.8836***
	(9.8073)	(9.4901)
GF	0.1356**	
	(2.3307)	
GF_{-1}		0.1083**
		(2.0882)
OPEN	0.0276*	0.0242
	(1.7355)	(1.6902)
HUMAN	0.9199	0.7584
	(1.5621)	(1.4311)
ES	−0.2748**	−0.2317*
	(−2.0854)	(−1.9413)
LABOUR	0.0059	0.0048
	(0.8907)	(0.9852)
R&D	−0.1050	0.1497
	(−0.1804)	(0.2311)
EDU	0.0349	0.0305
	(0.2236)	(0.2450)
AR(1)	0.007	0.008
AR(2)	0.779	0.681
Hansen	0.220	0.223
_cons	−0.0561	−0.0423
	(−1.6580)	(−1.6620)
N	270	270
adj.R^2		

Note: z-statistics are in parentheses in the table; *, **, and *** denote significant at the 10%, 5%, and 1% levels, respectively; AR (1) and AR (2) are used to test for the presence of first-order and second-order autocorrelation in the difference of the perturbation terms; all regression models are two-step and are estimated using a robust standard deviation-adjusted systematic GMM.

minimum value). GTI also shows similar results in magnifying the impact of green finance.

This reveals that both FinTech and GTI consistently enhance the positive impact of green finance on HQED across their respective percentiles. As the levels of FinTech and GTI increase, the marginal effects of green finance on HQED become significantly stronger, confirming the hypothesized moderating roles of these variables. This incremental pattern underscores the importance of integrating advanced FinTech and GTI to maximize the efficacy of green finance in promoting HQED.

5.5 Robustness check

To ascertain the empirical findings' robustness, this paper employs four distinct methods for robustness testing. First, the explanatory variable is substituted. Green finance encompasses tools such as green credit, green securities, green insurance, green investment, and carbon finance. Green credit is a pivotal instrument utilized by the government to incentivize financial institutions to channel resources and steer capital towards areas of environmentally friendly production. According to the research by Zhang et al. (2021), this study opts to use green credit as a substitute for green finance as the explanatory variable. Second, the sample interval is replaced. Considering the policy specificity of the municipalities, and referring to the approach of and Xu et al. (2020), the sample is re-estimated after excluding the four municipalities of Beijing, Tianjin, Shanghai, and Chongqing. Third, additional control variables are included. There are many objective factors affecting HQED, and to reduce the bias in estimation results due to omitted variable bias, this paper,

TABLE 7 Moderating effect test results.

	(1)	(2)	(3)	(4)
	HQED	HQED	HQED	HQED
GF	0.0982***	0.0743**	0.0979***	0.0800***
	(3.5508)	(2.6684)	(3.4955)	(2.8750)
FT	−0.0024	-0.0152		
	(−0.1217)	(-0.9507)		
GTI			−0.0007	−0.0043
			(−0.2198)	(−1.4042)
GF*FT		0.2622***		
		(5.1363)		
GF*GTI				0.0718***
				(3.5823)
OPEN	0.0870**	0.1156***	0.0871**	0.1092***
	(2.6400)	(4.0383)	(2.5711)	(3.5659)
HUMAN	0.7487	1.1310	0.7449	0.9702
	(0.5515)	(0.8164)	(0.5470)	(0.7141)
ES	0.3479	0.2203	0.3487	0.3295
	(0.7318)	(0.4475)	(0.7449)	(0.6636)
LABOUR	−0.0215	−0.0087	−0.0214	−0.0138
	(−0.8451)	(−0.3415)	(−0.8328)	(−0.5678)
R&D	3.0378**	3.4660***	3.0293***	3.2258***
	(2.6689)	(3.3965)	(2.8304)	(3.1835)
EDU	−0.0217	−0.0483	−0.0193	−0.0367
	(−0.2131)	(−0.4661)	(−0.1900)	(−0.3678)
Fixed effect	YES	YES	YES	YES
_cons	0.2664	0.1590	0.2648	0.2000
	(1.3996)	(0.8517)	(1.3781)	(1.1135)
N	300	300	300	300
adj.R^2	0.863	0.872	0.863	0.869

Note: *,** and *** indicate significance at the levels of 10%, 5%, and 1%, respectively. The values in brackets are t-statistics.

following Zhang et al. (2023), further controls for the level of urbanization. Fourth, data from the year 2012 is excluded. Since the China Banking Regulatory Commission issued the "Green Credit Guidelines" in 2012, prompting financial institutions in the banking sector to develop green credit, and since green credit is a major component and an important influencing factor of green finance, the data on green finance post-2012 is more effective, thus excluding the data for 2012. Columns (1), (2), and (3) show the estimation results with green credit as the substituted explanatory variable; Column (4) presents the results after redefining the sample interval; Column (5) shows the regression results after excluding the 2012 sample data, and column (6) reports the results after adding new control variables. According to the results in Table 8, whether substituting the explanatory variable, changing the sample interval, adding control variables, or excluding specific year data, the coefficient of green finance remains significantly positive, further affirming the robust and reliable role of green finance in promoting HQED.

5.6 Heterogeneity analysis

Considering the vast geographical expanse of China and the varying socioeconomic development across different regions, this study, based on the economic regional division method published

TABLE 8 Robustness test regression results.

	(1)	(2)	(3)	(4)	(5)	(6)
	Replace the explanatory variables			Replace the sample interval	Exclude the year 2012	Add control variable
GF				0.0720***	0.0882***	0.1056***
				(3.1541)	(3.0638)	(3.4825)
GC	0.0273*	0.0721***	0.0579***			
	(1.9424)	(4.8627)	(4.3356)			
Control variable	YES	YES	YES	YES	YES	YES
Time fixed effect	YES	NO	YES	YES	YES	YES
Regional fixed effect	YES	YES	NO	YES	YES	YES
_cons	0.2434**	0.1762	0.1183***	−0.0683	0.2771	0.2725
	(2.1382)	(1.3503)	(2.8898)	(−0.5763)	(1.4111)	(1.4048)
N	300	300	300	260	270	300
adj.R^2	0.840	0.782		0.877	0.854	0.865

Note: *,** and *** indicate significance at the levels of 10%, 5%, and 1%, respectively. The values in brackets are t-statistics.

by the National Bureau of Statistics of China in 2011, categorizes China into Eastern, Central, Western, and Northeastern regions[3]. This classification, based on socioeconomic characteristics including levels of economic advancement levels, industrial composition, and resource endowment, is more suitable for our research subject. Notably, variations in the levels of green finance exist among these regions, potentially influencing the quality of economic development differently. This study delves into the regional heterogeneity of this influence, with the results detailed in Table 9. The results demonstrate a significant positive correlation between green finance and HQED in the eastern region, marked by a coefficient of 0.1271, statistically significant at the 1% level. This implies that a 1% increment in green finance in the eastern region could enhance HQED by 0.1271%. This may be ascribed to the region's more mature financial markets and a richer array of green financial tools and services, effectively promoting green technologies and industries. Although the central region also shows a positive impact of green finance on HQED, denoted by a coefficient of 0.0635, it is significant only at the 5% level, suggesting a weaker influence compared to the eastern region. Nonetheless, it reaffirms the positive role of green finance in the central region's HQED. In contrast, the influence of green finance on HQED in the western region is not significant, with a coefficient of 0.0555, indicating that green finance has not yet become a significant driver of HQED in this region. Possible reasons include inadequate coverage of basic financial services, underdeveloped green finance products and mechanisms, and a weaker foundation for green industries. The northeastern region presents a unique case, with a coefficient of −0.0238 for green finance's impact on HQED. Although not significant, the negative coefficient may indicate that the relationship between green finance and HQED is not consistently positive in this region.

It is noteworthy to discuss that some control variables exhibit negative significance. Firstly, the impact of the energy structure in the Western region on HQED is negatively significant. The energy structure is reflected through the proportion of electricity consumption in total energy consumption. The negative coefficient might stem from the Western region's reliance on traditional energy sources like coal (Mi and Sun, 2021; Hongjun et al., 2023). Additionally, a high ratio of electricity consumption may indicate a higher level of industrialization, which could entail environmental pollution and excessive resource extraction, contradicting the principles of HQED that emphasize sustainability and eco-friendliness. Secondly, in the Eastern and Central regions, the level of the workforce (measured by the number of employed individuals) negatively influences HQED. This could be attributed to the lack of corresponding increases in labor productivity despite the rising labor force numbers in China, a consequence of demographic changes in the working population (Wu et al., 2023). This means that the increase in labor has not translated into more efficient production and services. Furthermore, the Eastern and Central regions may face issues of labor surplus, leading to inefficient employment and overcapacity, which are detrimental to HQED. Thirdly, financial support for education in the Eastern region has a negative impact on HQED. This could be due to the delayed effects of education investment, which typically takes a long period to manifest in economic development and may not yield immediate visible outcomes (Hanushek and Woessmann, 2010). Alternatively, it could be because an increase in education spending might crowd out investments in other areas more directly impacting HQED, such as technological innovation and environmental protection.

3 To accurately reflect the socioeconomic development status of different regions in China, the National Bureau of Statistics of China released the "Method for Dividing Eastern, Central, Western, and Northeastern Regions" in 2011. This method divides China's economic regions into four major areas: Eastern, Central, Western, and Northeastern.

TABLE 9 Regression results based on regional heterogeneity sample.

	Eastern region	Central region	Western region	Northeastern region
	HQED	HQED	HQED	HQED
GF	0.1271***	0.0635**	0.0555	−0.0238
	(2.8737)	(2.2778)	(1.1359)	(−0.2848)
OPEN	0.0614***	0.0561	0.2373***	−0.3829*
	(3.7679)	(0.7480)	(5.7351)	(−1.8128)
HUMAN	−0.5237	−1.7767**	−1.0185	7.4427
	(−0.3066)	(−2.3045)	(−1.0764)	(0.9738)
ES	0.6453	0.1649	−1.3523***	5.4311
	(1.3915)	(0.4373)	(−2.8597)	(0.6587)
LABOUR	−0.0810***	−0.0385**	0.1394***	−0.0241
	(−3.2905)	(−2.5863)	(3.4735)	(−0.2467)
R&D	3.3501***	4.0992***	1.5153	8.6343**
	(3.9639)	(6.1731)	(1.5595)	(2.3247)
EDU	−0.2595**	0.1359*	−0.0745	0.3820
Fixed effect	(−2.2310) YES	(1.7104) YES	(−0.5494) YES	(0.6193) YES
_cons	0.8306***	0.4205***	−0.8622***	0.0144
	(3.9605)	(3.1139)	(−3.0339)	(0.0201)
N	100	60	110	30
adj.R^2	0.834	0.982	0.886	0.839

Note: *,**, and *** indicate significance at the levels of 10%, 5%, and 1%, respectively. The values in brackets are t-statistics.

Overall, the impact of green finance on the HQED of the eastern, central, western, and northeastern regions exhibits significant regional disparities. The eastern region benefits the most conspicuously, succeeded by the central region, while the influence of green finance is comparatively weaker in the western and northeastern regions. This conclusion, that the promotion effect of green finance on high-quality economic development is more significant in the eastern and central regions of China compared to other regions, corresponds with the findings of Li (2023). However, it differs slightly from the findings of Yang (2023), who also acknowledged the heterogeneity of the impact of green finance on HQED but believed that the influence was greater in the eastern and western regions than in the central region. This contrast highlights the complexities and varying perspectives in current research, further demonstrating the spatial heterogeneity of the impact of green finance on HQED. This disparity likely reflects the differences in economic development levels, financial market maturity, and green finance policies and practices among these regions. This underscores the need for not only strengthened policy coordination between regions in advancing green finance but also for taking into consideration the unique characteristics of each region to maximize the benefits of green finance. This disparity likely reflects the differences in economic development levels, financial market maturity, and green finance policies and practices among these regions. This underscores the need for not only strengthened policy coordination between regions in advancing green finance but also for taking into consideration the unique characteristics of each region to maximize the benefits of green finance.

After analyzing regional heterogeneity, we further examined the moderating effects of FinTech and GTI on the impact of green finance across different regions. The results indicate that, although the interaction terms between green finance and both FinTech and GTI are significantly positive in the eastern region, the core coefficient of green finance becomes insignificant after including the moderating terms. This suggests that while FinTech and GTI exhibit significant moderating effects in these regions, they may diffuse the direct impact of green finance, rendering its independent effect insignificant. In contrast, in the central, western, and northeastern regions, such moderating effects are not significant. This may be due to the lower development levels of FinTech and GTI in these areas, as well as the inadequate infrastructure for financial services and technological support, which fails to significantly enhance the efficacy of green finance. Detailed results are presented in Supplementary Appendix SB2.

6 Conclusions and suggestions

6.1 Research conclusions

In the context of the global environmental challenges and economic development needs of the 21st century, green finance, as

a vital instrument for supporting sustainable development, has increasingly attracted attention for its role in promoting HQED. This study analyzes panel data from 30 provinces in China spanning from 2012 to 2021, examining the relationship between green finance and HQED across Chinese regions from the perspectives of FinTech and green technological innovation (GTI) and conducting an analysis of regional heterogeneity. The outcomes reveal that: Firstly, the enhancement of green finance significantly fosters HQED, exerting a notable promotional effect on it. Secondly, the mechanism test further validates that FinTech and GTI are crucial pathways through which green finance promotes HQED, indeed playing a positive moderating role in the relationship between green finance and HQED. Finally, The impact of green finance on HQED is characterized by marked regional disparities. The eastern region benefits the most, succeeded by the central region, while the influence of green finance is relatively weaker in the western and northeastern regions. Lastly, the moderating effects of FinTech and GTI on the impact of green finance on HQED also exhibit regional heterogeneity.

6.2 Policy implications

Firstly, fostering green finance development with a long-term vision requires coordinated efforts from policymakers and financial institutions. Government agencies should prioritize the development of green finance by creating favorable regulatory frameworks and offering incentives for green financial products and services, including green credit, green securities, green investments, and green insurance. Financial institutions should intensify the promotion of these products to facilitate broader market adoption. Given the lag effect of green finance on HQED, it is advised to consider long-term benefits in policy formulation and project evaluation rather than relying solely on short-term economic indicators. Additionally, establishing a comprehensive tracking and evaluation mechanism is recommended to continually monitor and assess the long-term impacts of green finance projects.

Secondly, maximizing the catalytic role of GTI and FinTech in bolstering green finance for HQED requires active support from both the government and private sector. Government agencies should provide grants and subsidies to encourage corporate investment in GTI and FinTech. Companies should leverage technologies like big data, cloud computing, blockchain, and artificial intelligence to enhance the transparency and tracking capabilities of green finance projects, thereby improving the efficiency and coverage of green financial products and services. This approach will better leverage the potential of GTI and FinTech in facilitating the role of green finance in HQED.

Thirdly, formulating differentiated strategies based on regional heterogeneity. Given the observed regional disparities in green finance's impact across the Eastern, Central, Western, and Northeastern regions in China, it is imperative for policymakers and financial bodies to implement more precise regional strategies. For the Eastern and Central regions, government agencies should provide further support for green finance initiatives through subsidies, tax incentives, and public-private partnerships to consolidate and expand its role in HQED. For the Western and Northeastern regions, despite the less significant promotional effects observed, this does not diminish the importance of green finance in economic development. It is recommended to analyze the reasons behind the insufficient impact of green finance in these regions such as lack of funds, technological backwardness, immature markets, etc., and provide tailored policy support and financial services to improve green finance and the capacity for HQED in these areas.

6.3 Research limitations and future prospects

This study primarily employed empirical methods and variable data to explore green finance, facing limitations due to a scarcity of relevant data and a narrow geographic focus on China. This approach restricted the depth and breadth of our empirical analysis, offering a limited perspective on a subject with global implications. Future research should aim for a more comprehensive understanding by utilizing a wider array of data and expanding the geographical scope, thereby enabling a deeper investigation into the nuances and complexities of how green finance contributes to HQED.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

YX: Conceptualization, Data curation, Formal Analysis, Methodology, Software, Validation, Writing–original draft, Writing–review and editing. ZD: Conceptualization, Formal Analysis, Funding acquisition, Methodology, Supervision, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2024.1414365/full#supplementary-material

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How to maintain environmental integrity when using state support and the VCM to co-finance BECCS projects - a Swedish case study

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Limiting global warming to close to 1.5°C by 2100 requires deep and rapid greenhouse gas emission reductions and carbon dioxide removals (CDR) on a massive scale, presenting a remarkable scaling challenge. This paper focuses on the financing of bioenergy with carbon capture and storage (BECCS) in Sweden. BECCS is one of the most prominent CDR methods in 1.5°C-compatible global emission scenarios and has been assigned a specific role in Swedish policy for net-zero. A Swedish state support system for BECCS based on results-based payments is planned. Furthermore, demand for CDR-based carbon credits is on the rise on the voluntary carbon markets (VCM) for use towards voluntary mitigation targets. Risks involved with the current Swedish policies are analysed, specifically for the co-financing of BECCS by the planned state support and revenues from the VCM. We find that with the current policies, state support systems will subsidise carbon credit prices on the VCM. We argue that such subsidisation can lower decarbonisation efforts by lowering the internal carbon price set by actors, thus undermining environmental integrity. It is concluded that proportional attribution should be applied, i.e., attributing mitigation outcomes to the state support and VCM revenue in proportion to their financial contribution to the CDR achieved. The attribution analysis should be accompanied by adjustments in national greenhouse gas accounting so that mitigation outcomes that are issued as carbon credits and used for offsetting are not double claimed (i.e., not used by both a nation and a non-state actor on the VCM towards their respective mitigation targets). If proportional attribution and adjustments in national GHG accounting are not implemented, the credibility and environmental integrity of offsetting claims made by carbon credit users are eroded. We recommend that action is taken to operationalise and implement proportional attribution to allow for co-financing of BECCS projects while maintaining environmental integrity. Wider implications for our recommendations beyond the case of Swedish BECCS are also analysed.

KEYWORDS

BECCS, voluntary carbon markets, internal carbon price, co-financing, attribution, corresponding adjustment

1 Introduction

The IPCC AR6 WGIII report analyses scenarios which limit global warming to 1.5°C by 2100, emphasising the need for rapid and deep greenhouse gas (GHG) reductions and achieving global net-zero CO_2 emissions by mid-century (IPCC, 2022). These scenarios rely on substantial carbon dioxide removal (CDR) for three purposes, namely i) to reduce net emissions from current levels faster, ii) to counterbalance residual emissions in order to enable net-zero emissions, and iii) for achieving global net-negative emissions in order to achieve the 1.5°C goal by 2100, even with a temporary overshoot. The annual rates of carbon removal projected for the end of the century approach half of the prevailing global CO_2 emissions, which underscores the imperative nature and substantial significance of CDR in achieving the 1.5°C target stipulated in the Paris Agreement (IPCC, 2022).

Current financing for CDR is not enough, as evident by the so-called CDR gap, illustrating the difference between actual and necessary CDR deployment to reach the temperature target of the Paris Agreement (Smith et al., 2023). Previous studies have raised the question "*who shall pay for CDR?*" (Honegger et al., 2021; Zetterberg et al., 2021; Hickey et al., 2023; Honegger, 2023). To date, private voluntary funding has been the main source of funding for CDR (Honegger, 2023). However, the majority of currently operational mechanisms in carbon markets mainly support lower-cost conventional CDR methods that build on so-called nature-based solutions (Hickey et al., 2023), while novel (non-nature-based) CDR methods with more durable carbon storage have received less financing. In the most recent years, government financing schemes are being prepared and deployed to promote deployment of novel CDR methods, for example, in Denmark, Norway, Sweden, the United Kingdom, and the US (DESNZ, 2023; Grupert and Talati, 2023; Hickey et al., 2023; Möllersten et al., 2023). Without a significant growth in financing, CDR will fail to scale sufficiently. Therefore, an "all hands on deck" approach features in policy discussions, where both public and private finance can contribute to upscaling CDR (Honegger et al., 2021; Honegger, 2023; Möllersten and Zetterberg, 2023).

While governments must take the main responsibility for the timely funding and scaling of CDR within compliance frameworks, private funding through the voluntary carbon markets (VCM) can make important contributions in terms of creating early market demand signals and trigger investment (Allen et al., 2020; Bernasconi, 2021; Honegger, 2023; Puro.earth, 2023). Non-state actors such as corporations are increasingly engaging in voluntary climate target setting (Net Zero Tracker, 2024; SBTi, 2024), including the use of carbon credits as part of voluntary targets (Blaufelder et al., 2020). Moreover, there is a demand-shift on the VCM towards carbon credits representing durable CDR (Donofrio and Procton, 2023; Michaelowa et al., 2023). The demand for such carbon credits can be expected to grow, since an increasing number of standard-setters and scholars are demanding offsetting based on permanent CDR specifically in the context of net-zero claims (Allen et al., 2020; SBTi, 2021; Fankhauser et al., 2022; ISO, 2022; Race to Zero, 2022; United Nations, 2022). The demand-shift and a projected growth of the VCM (TSVCM, 2021; Chyka, 2023) combined, make the VCM a future potentially significant contributor to CDR financing and CDR gap closure. Initial VCM transactions involving bioenergy with carbon capture and storage (BECCS) include Microsoft entering into off-take agreements for carbon credits with Danish Ørsted and Swedish Stockholm Exergi (Romm, 2023; Beccs Stockholm, 2024).

This paper explores challenges associated with the interaction between public results-based finance and VCM finance for BECCS, one of the most prominent CDR methods in IPCC scenarios compatible with attaining the Paris Agreement long-term target. Sweden has been selected for the study. The Swedish government is preparing the introduction of results-based state support for CDR from BECCS (Government of Sweden, 2023). At the same time, a large number of private actors are pursuing preparations to actively participate as sellers of BECCS carbon credits on the VCM (Fridahl and Lundberg, 2021; Beccs Stockholm, 2023). Historically, the VCM have primarily sourced carbon credits in jurisdictions without formal national GHG mitigation obligations and typically only the carbon credit buyers have had an interest in claiming the underlying mitigation outcome (Hermwille and Kreibich, 2016). The co-financing of projects that combine government support with VCM finance for the same mitigation outcome, in a setting with national GHG mitigation targets, is a relatively new and untested situation. However, such situations are becoming increasingly common since the Paris Agreement entered into force (Ahonen et al., 2022). In the Swedish context, a policy discussion has surfaced which centres around the Swedish state's and carbon credit buyers' respective rights to claim the mitigation outcomes from co-financed BECCS projects. A main area of contention in the discussion is whether the double claiming of mitigation outcomes towards existing national and corporate mitigation targets should be eligible (Möllersten and Zetterberg, 2023). "Double claiming" refers to a situation where the same emission reduction or carbon removal (i.e., the same mitigation outcome) is claimed by two different entities or for two different purposes, for example, for two different targets (Schneider and La Hoz Theuer, 2019). In this case, the double claiming would occur between the Swedish state claiming the mitigation outcome towards the Swedish national target and a carbon credit buyer claiming the mitigation outcome towards its voluntary climate target. Environmental integrity risks associated with the policy choice of whether or not to allow double claiming have already been analysed in the literature (Kreibich and Hermwille, 2021; Ahonen et al., 2022; Ahonen et al., 2023). In the context of co-financing and double claiming of mitigation outcomes, based on a literature review, we identify an environmental integrity risk that has previously not been addressed in the literature and propose how the risk may be avoided.

In section 2, we outline the evolution of the VCM from the Kyoto era until now in order to provide a background on the rationale for the use of carbon credits for offsetting and the current Swedish policy debate. In section 3, we introduce the case study of Sweden, specifically the BECCS potential and recent developments of the Swedish policy context related to government BECCS support and the VCM. In section 4, we analyse environmental integrity risks associated with the current Swedish policies and suggest alternative pathways. In section 5, actionable recommendations are presented based on the Swedish case-study.

2 Voluntary carbon markets and the transition from the Kyoto Protocol to the Paris Agreement

2.1 Environmental integrity on compliance markets under the Kyoto Protocol

Carbon credit markets, established under the Kyoto Protocol through baseline and credit mechanisms, were introduced to enhance flexibility and cost-efficiency of compliance for developed countries with quantified GHG mitigation commitments (Ahonen et al., 2022). Two project-based mechanisms, namely the Clean Development Mechanism (CDM) and the Joint Implementation (JI), facilitated international transfer of mitigation outcomes. This meant that a "buyer country" could contribute to financing mitigation projects in another "host country" through the purchase of carbon credits, and that the buyer country could count the mitigation outcome towards its own Kyoto mitigation commitment, thus achieving part of its goal outside national boundaries (Michaelowa et al., 2019). The atmosphere sees no national boundaries, meaning that the same climate benefit could be achieved anywhere where there is mitigation potential. It would thus be economically rational to use international transfer mechanisms if mitigation outside the buyer country's national borders was more cost-efficient. The CDM was a mechanism where host countries were developing countries without quantified GHG mitigation commitments, and the JI was a mechanism in which both the buyer country and the host country had quantified mitigation commitments (Michaelowa et al., 2019).

Both the CDM and the JI emphasised the importance of maintaining environmental integrity during international transfer of mitigation outcomes in the sense that meeting a Kyoto mitigation commitment through an international transfer would not result in a global increase of emissions compared to if the commitment was met without the international transfer (Schneider, 2009). Phrased differently, if the global net GHG emissions to the atmosphere would be lower if a buyer country reached its commitment within national borders and thus without any international transfer, the environmental integrity of the mechanisms could be questioned. Key provisions for ensuring environmental integrity included establishing conservative baselines, demonstrating additionality and preventing double counting (Schneider et al., 2015; Michaelowa et al., 2019). If the mitigation project would not have happened without the opportunity for revenue from the sale of carbon credits, the project was deemed additional. Additionality was thus important to ensure that carbon finance would not be wasted on projects that would have been realised either way. To avoid double claiming, a form of double counting, the CDM and the JI necessitated different approaches. Double claiming effectively undermines the environmental integrity of international transfer mechanisms, since the global net GHG emissions would have been lower if both countries had achieved their targets inside national boundaries, i.e., without international transfers. For the JI, where both the buyer country and the host country had mitigation commitments, double claiming was avoided through the surrender of assigned amount units (AAUs), which meant that only the buyer country would count the mitigation towards its commitment (Ahonen et al., 2022). Under the CDM, which was also the most successful mechanism in terms of total international transfers, double claiming was a non-issue, since only the buying country had a GHG mitigation commitment, while the host country did not have any quantified target to count the mitigation towards.

2.2 The evolution of voluntary carbon markets during the Kyoto period and beyond

Private carbon crediting standards emerged in parallel with the Kyoto mechanisms to cater to demand for credits from the VCM (Ahonen et al., 2022). Despite lacking international oversight, the emerging VCM broadly embraced the principles for safeguarding environmental integrity observed in compliance markets, including additionality and avoidance of double counting (Kreibich and Hermwille, 2021). This meant that, effectively, while international carbon trading on compliance markets was a zero-sum game, the legitimacy of offsetting claims on the VCM required that the use of carbon credits should contribute to increased global mitigation ambition. This is evident if one considers the following key circumstances: firstly, the voluntary use of carbon credits for offsetting purposes would not be counted towards the mitigation commitment of the offsetting actor's home country; secondly, the mitigation outcome underlying the carbon credits were additional and, in addition, associated with surrender of AAUs if carbon credits from JI projects were used for the offsetting. In other words, the home country of the offsetting company would not have to do less to comply with its Kyoto commitment and at the same time additional mitigation outcomes would be achieved elsewhere, thus raising global ambition beyond the collective ambition level of national mitigation commitments. Notably, the Voluntary Carbon Standard (VCS), the largest private carbon crediting standard during the time of the Kyoto Protocol, followed the JI principle for projects realised in developed countries, requiring an official document from the host country certifying that an amount of AAUs equivalent to the number of credits to be issued had been cancelled (Kreibich and Hermwille, 2021).

Since the Paris Agreement in 2015, all signatory countries have set climate targets, meaning that mitigation projects in any host country, which is a signatory to the Agreement, could be included in a national mitigation target. Although all countries have mitigation targets, some have opted to adopt targets that are not economy-wide. Therefore, additional mitigation outcomes in a sector outside a national emission target would still constitute a global ambition increase and thus respect the logic on which voluntary use of carbon credits for offsetting purposes was based under the Kyoto era. The same can be said about mitigation outcomes from activities that have not been incorporated in the framework for national GHG inventories, and are thus not visible in national GHG reporting and accounting, meaning that countries cannot report the mitigation towards their target. If, however, the additional mitigation outcome, underlying carbon credits used for voluntary offsetting purposes, belong in a sector that is covered by a national mitigation target, there would be no global ambition increase since the host country could do less to achieve its targets, unless the carbon credit is associated with a "corresponding adjustment" - the Paris

TABLE 1 Approaches for the use of carbon credits in case of co-financing CDR, adapted from Kreibich and Hermwille (2021).

Approach	Type of credit	Claims
1	Carbon credit for national mitigation target support	Projects contributing to a host country's national mitigation target but ineligible for offsetting purposes. Claims to have contributed to the host country's mitigation target can be made ("contribution claims")
2	Carbon credits eligible for offsetting without corresponding adjustment	Credits used for offsetting claims and counted toward the host country's mitigation target, raising legitimacy concerns and reputational risks since offsetting would not be based on mitigation beyond existing national mitigation targets
3	Carbon credits eligible for offsetting with corresponding adjustment	The only solution ensuring environmental integrity, requiring the host country to exclude credit-related mitigation outcomes from its national mitigation target. Offsetting would be based on mitigation beyond national targets

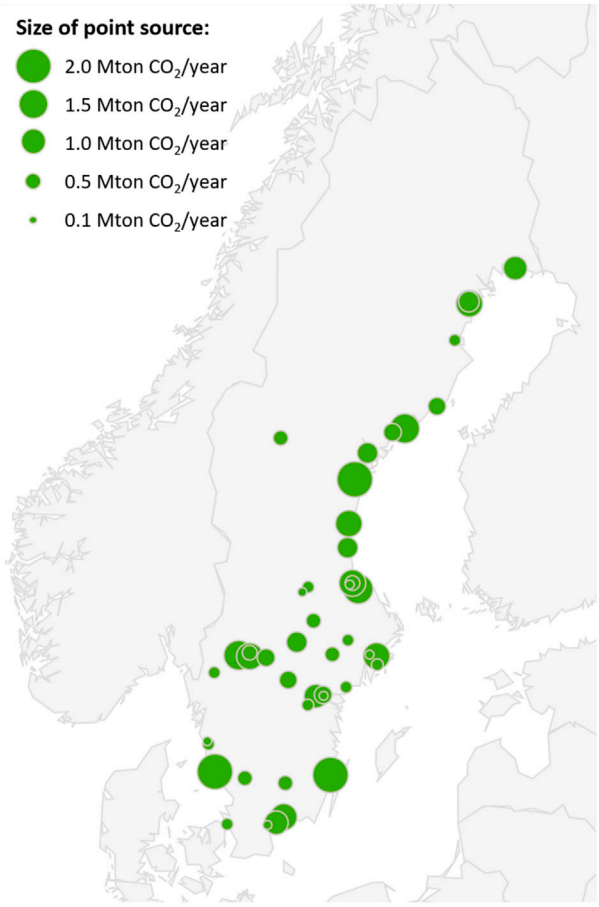


FIGURE 1
Biogenic point source emissions in Sweden. Biogenic point sources larger than 0.1 Mton CO_2 have been included. Point sources with more than 10% fossil emissions have been excluded. Emissions data from 2022 was used. The sum of all illustrated biogenic point source emissions amount to about 28 Mton CO_2. Assuming a capture rate of 90%, the biogenic capture potential from these point sources amount to about 25 Mton CO_2 annually.

equivalent of AAU surrender. Kreibich and Hermwille (2021) have proposed three alternative approaches for the use of carbon credits that are relevant to the case of co-financing of mitigation through results-based state support and carbon credit revenue from the VCM in the context of economy-wide targets, and thus applicable to Sweden, listed in Table 1.

The categorisation of carbon credit use cases presented in Table 1 provides a conceptual background for understanding the current Swedish policy discussion which is elaborated in section *3.2 Swedish policy for state support for BECCS and its relation to the VCM* concerning the interaction between results-based state support for BECCS and the emerging VCM for carbon credits based on CDR. The central issue revolves around whether and why mitigation outcomes should go beyond existing national mitigation targets, i.e., constitute a global ambition increase, when carbon credits based on the same mitigation outcome serve as the foundation for actors' offsetting claims. Compared to what has been common practice on the VCM, it would constitute a reduction in ambition to transition from requiring offsetting claims only in accordance with approach 3) to also allowing offsetting in line with approach 2) in the above list in Table 1, which is a poignant fact considering the number of stakeholders arguing for allowing approach 2) (see for example, Stockholm Exergi, 2022; Swedenergy, 2022; Stenström et al., 2024). Although this background is required for understanding the current Swedish discussion, stakeholder efforts to increase acceptance for approach 2) is not the main focus of this paper, nor is the truthfulness of claims which has been discussed already in literature (Ahonen et al., 2022; Ahonen et al., 2023; Möllersten and Zetterberg, 2023), but rather previously unidentified effects on voluntary decarbonisation efforts from the current policies regarding co-financing of Swedish BECCS projects.

3 Case study - BECCS in Sweden

3.1 Swedish BECCS potential

Sweden has a significant potential to capture biogenic CO_2 from point source emissions, mainly from the pulp and paper industry and heat and power production (Rodriguez et al., 2021). Based on data from Swedish Environmental Protection Agency (2023), Figure 1 illustrates biogenic point source emissions in Sweden larger than 0.1 Mton CO_2 annually. Point sources with a higher share than 10% fossil emissions have been excluded, meaning that waste incineration plants are not included. The rationale for only including point sources with over 90% biogenic emissions is because it is uncertain whether there will be a demand from the VCM for carbon credits from waste incineration plants, or other plants with a relatively high share of fossil emissions. The sum of biogenic emissions from the point sources included in Figure 1 is about 28 Mton CO_2 annually. Assuming a 90% carbon capture rate, the

biogenic capture potential from these sources amount to about 25 Mton CO_2 per year. If instead all point sources above 0.1 Mton CO_2 are included, regardless of the biogenic share, the biogenic emissions annually amount to 33 Mton CO_2, implying a total biogenic capture potential of 30 Mton CO_2 per year.

There is theoretical potential for geological storage of CO_2 in Sweden (SGU, 2016), but a combination of lack of experience, regulatory hindrances, such as the HELCOM convention which prohibits geological storage of CO_2 in the Baltic Sea, and long lead-times implies that captured CO_2 needs to be exported for storage at least in the short-term (SGU, 2016; Fridahl et al., 2020; Möllersten et al., 2023). In close proximity, Norway is pioneering initiatives providing CO_2 storage as a service below the North Sea. Furthermore, Denmark is making preparations for CO_2 storage on- and off-shore and is increasingly recognized as a prospective geological CO_2 storage service provider. Additionally, Iceland is in the preparatory stages to offer services based on *in situ* CO_2 mineralisation, involving its dissolution in water and subsequent injection into basaltic subsurface layers (Möllersten et al., 2023). There are, thus, multiple potential storage places in neighbouring countries where CO_2 from Swedish point sources potentially could be sequestered.

3.2 Swedish policy for state support for BECCS and its relation to the VCM

The Swedish government is planning for a state support system based on reverse auctions to enable implementation of BECCS (Möllersten and Zetterberg, 2023; Government of Sweden, 2023). In the reverse auctions, the state is the buyer of CDR from BECCS and actors with BECCS potential make bids. The lowest bid per ton of stored CO_2 wins, and is granted state support for 15 years to capture and geologically store biogenic carbon dioxide (Government of Sweden, 2023). Thus far, 36 billion Swedish SEK have been allocated towards the support system. The intention is to use the resulting CDR towards national mitigation targets for counterbalancing residual emissions, ultimately to attain net-zero GHG emissions by 2045 at the latest.

The Swedish BECCS support system is being developed against the backdrop of a policy discussion that has already been mentioned briefly in previous sections. Several Swedish companies in the district heating sector who could potentially deploy BECCS have promoted, both individually and jointly through their business organisation Swedenergy, an approach which allows that BECCS mitigation outcomes could be awarded results-based payments from the Swedish state and be counted towards the Swedish national mitigation target, while the same mitigation outcomes would make the basis for issuance of carbon removal credits that could be sold on the VCM to be used by purchasing entities towards offsetting claims. Others, for example, the Swedish Energy Agency and scholars, have argued that such double claims would not be aligned with environmental integrity principles (Möllersten and Zetterberg, 2023). In 2023, a commission of inquiry recommended that the Swedish government should enable the additional private financing of BECCS by abstaining from claiming privately financed CDR from BECCS towards Swedish mitigation targets (Hassler, 2023). Moreover, in the EU beyond Sweden, seven EU member states made a joint statement in December 2023 which conveys the message that the credibility of offsetting claims requires that *"The carbon credits represent mitigation outcomes that are not counted by the host country (as part of their national climate targets)."* (Government of the Netherlands, 2023).

In December 2023, the Swedish government proposed in its strategic climate action plan that actors receiving state support for BECCS should be allowed to sell carbon removal credits on the VCM (Government of Sweden, 2023). It is stated that Sweden will claim the resulting CDR towards Swedish mitigation targets, contrary to the recommendation by Hassler (2023). It is further suggested that buyers of carbon removal credits should be able to claim the mitigation outcome that they represent towards their own voluntary climate targets. Therefore, it is suggested that the buyers of negative emissions shall make clear in their climate reporting that the negative emission is contributing to Sweden's possibility to reach its climate targets (Government of Sweden, 2023).

Currently, the most common voluntary climate targets include carbon neutrality and net-zero emissions, typically relying on the voluntary use of carbon credits for offsetting in addition to the mitigation of GHG in the target-setting actors' value chains (Blaufelder et al., 2020). Since the type of voluntary target eligible to claim the negative emission is not specified by the Swedish government, it cannot be ruled out that the Swedish government finds it appropriate for the carbon removal credits to be used for offsetting purposes. It is, therefore, justified to assume that the Swedish government is willing to support the potential use of carbon removal credits in accordance with approach 2 in Table 1, resulting in double claiming since both a state and an actor purchasing carbon credits on the VCM use the same mitigation outcome towards their respective mitigation targets.

Since BECCS is in its infancy and expected to be expensive with cost range estimates between 100 and 200 USD/ton CO_2 towards mid-century (Fuss et al., 2018), sharing the cost with the VCM seems judicious in order to avoid high public expenditures. Even with the lower end cost estimation, the budget of the Swedish support system would yield CDR of 2.4 Mton CO_2 annually which is significantly lower than the expected level of residual emissions in 2045 of 10.7 Mton CO_2 when Sweden is to reach net-zero emissions (Government of Sweden, 2023). Co-financing without double claiming could be achieved with contribution claims where the carbon credit buyer does not make an offsetting claim but rather communicates that the funding contributes to achieve the Swedish climate targets (i.e., approach 1 in Table 1). However, the demand for carbon credits eligible only for contribution claims is currently unknown. Meanwhile, the demand for offsetting claims is expected to stay strong. Therefore, it seems from the current policies that the Swedish government is hoping that the VCM might help close the financing gap, by accepting double claims (approach 2 in Table 1).

4 Analysis of environmental integrity implications of Swedish BECCS policy

The inclination of the Swedish government to rely on the VCM as a means to help finance CDR necessary to attain the Swedish net-

zero target and accept double claiming comes with profound and widespread ramifications. Notably, allowing double claiming of co-financed CDR effectively means that the Swedish state is subsidising the carbon credit price on the VCM (Möllersten and Zetterberg, 2023). This is because the buyer of carbon credits can claim 100% of the mitigation outcome, while financing less than 100% (since part is financed by the state). In section *4.1 Internal carbon price*, we will discuss possible implications of subsidised carbon removal credits on voluntary decarbonisation efforts. In section *4.2 Attribution*, we suggest an alternative pathway for allowing co-financing of BECCS projects without double claiming, thus enabling the environmental integrity level of approach 3) mentioned in Table 1 to be attained. In section *4.3 Corresponding adjustment*, we identify a policy gap that needs to be addressed for the solution suggested in section *4.2 Attribution* to become practicable. In section *4.4 Alternative pathways until corresponding adjustments are enabled* we suggest how to bridge the policy gap until it is filled, in order to use attribution as a solution.

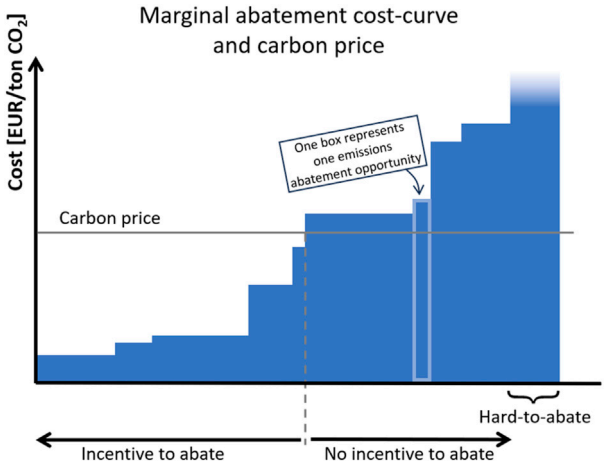


FIGURE 2
Marginal abatement cost-curve and carbon price. The higher the carbon price, the higher incentive to reduce emissions. Note that some actors might have emissions that are hard- or impossible-to-abate, meaning that even an extremely high carbon price would not reduce those emissions due to technical limitations.

4.1 Internal carbon price

Putting a price on GHG emissions, commonly known as "carbon pricing", to internalise the damage of GHG emissions features in many climate policies. In Sweden, a tax on fossil CO_2 emissions was introduced in 1991. In 2023, the Swedish CO_2 tax was 122 EUR/ton CO_2. Since 1990, partly due to the CO_2 tax, Swedish emissions have decreased by 33% (Government Offices of Sweden, 2024). Another way of putting a price on GHG emissions is through a cap-and-trade system, such as the European Union (EU) emission trading system (ETS). Since 2005, the EU ETS has contributed to decreasing emissions from power and industry plants by 37% (European Commission, 2024). The permit price in the EU ETS is 71 EUR/ton CO_{2e} at the time of writing (2024-06–12), and has varied between 50 to almost 105 EUR/ton CO_{2e} during the last 2 years (Trading Economics, 2024).

Carbon pricing increasingly features voluntarily among actors as well (Bartlett et al., 2021). When a carbon price is set voluntarily, it is called an internal carbon price (ICP). Previous studies have shown multiple motivations for setting an ICP, for example, to mitigate risks associated with high carbon intensity in anticipation of national policies, to reach voluntary climate targets, to incentivise efficiency improvements or other changes that reduce operating costs, or to respond to outside pressure for carbon management (Harpankar, 2019; Bento and Gianfrate, 2020; Gorbach et al., 2022; Trinks et al., 2022). Previous studies have also shown that actors with an ICP decarbonize faster and deeper in comparison with their counterparts that do not have an ICP (Benedicto, 2022; Zhu et al., 2022; Qin et al., 2023).

The most common type of ICP is a so-called "shadow price" which informs investments and deters high-carbon investments, thus reducing emissions in the long-run compared to business as usual. However, shadow prices provide little short-term incentive to reduce emissions (Harpankar, 2019; Gorbach et al., 2022). Conversely, an "internal carbon fee" is a type of ICP which is associated with actual payments for ongoing emissions. An internal carbon fee provides a short-term incentive to decrease emissions as well as a longer-term incentive (Harpankar, 2019; Gorbach et al., 2022; Höglund, 2022).

As part of setting voluntary science-based targets (see, e.g., SBTi (2021)), Schallert et al. (2020) recommend implementing an internal carbon fee to channel finance for mitigation within and/or outside of the value chain. If the ICP is higher than the company's marginal abatement cost, emission reductions should be made across its value chain. Otherwise, the finance generated from the ICP should finance mitigation outside of the company's value chain (Schallert et al., 2020). The higher the ICP, the higher the incentive to reduce emissions within the value chain (Qin et al., 2023), as illustrated in Figure 2, leading to lower remaining emissions within an actor's value chain, and more carbon finance generated per unit of remaining emission.

The ICP can be set in multiple ways. One way is to set a total financial commitment for emissions abatement during a period and divide the total number with the company's remaining emissions during the same period, thus revealing the implied ICP (Schallert et al., 2020). Another way is to base the ICP on external factors, such as the social cost of carbon, policy carbon prices such as taxes or trading systems, the price of carbon credits on the VCM, or the cost of permanent carbon removals (Harpankar, 2019; Höglund, 2022; Modi et al., 2023). The social cost of carbon reflects the societal cost of GHG emissions and has recently been estimated by Rennert et al. (2022) to 185 USD/ton CO_2 (in 2020 USD). The US Environmental Protection Agency estimates the social cost of carbon to be between 120 and 340 USD/ton CO_2 (in 2020 USD), depending on the discount rate (EPA, 2023). Carbon taxes and trading system permits differ between regions. The Swedish carbon tax and EU ETS permit price have already been mentioned in the beginning of this section. The carbon credit price on the VCM was on average 7.37 USD/ton CO_2 in 2022, but there is a large price range (Donofrio and Procton, 2023). The cost of permanent carbon removal depends on the CDR method.

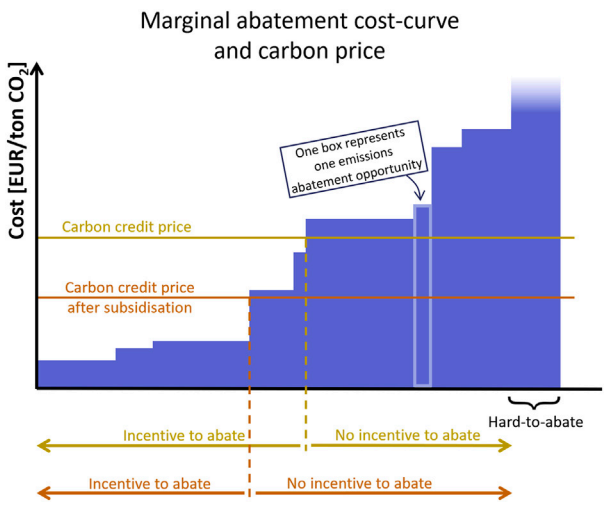


FIGURE 3
Marginal abatement cost-curve and carbon credit price. The higher the carbon credit price, the higher incentive to reduce emissions. Note that some actors might have emissions that are hard- or impossible-to-abate, meaning that even an extremely high carbon price would not reduce those emissions due to technical limitations.

As an example, the cost of BECCS is, as already mentioned, estimated to 100–200 USD/ton CO_2 towards mid-century (Fuss et al., 2018). Currently, the quoted market price for BECCS carbon credits is 300 EUR/ton CO_2 (Smith et al., 2024).

Combining co-financing through state support and carbon revenue from the VCM with double claiming means that the state is, in effect, subsidising the VCM, making the carbon credit prices lower than they would have been if actors on the VCM only could claim the share they paid for. As mentioned, there are multiple ways to set an ICP, but it is particularly likely that the carbon credit price of permanent removals will influence voluntary ICPs since influential standard-setters for voluntary targets require compensation for residual emissions by permanent removals specifically (SBTi, 2021; ISO, 2022). If the subsidised price of BECCS credits influences and lowers the ICP set by actors, this has far-reaching consequences since: i) the decarbonisation rate might be lower since the incentive to abate is reduced, and ii) the resulting residual emission level might be higher if a lower cost of purchasing permanent removals reduces what is perceived as a prohibitive cost of abatement. The potential effect of the subsidised BECCS credit price is illustrated in Figure 3.

4.2 Attribution

There is limited experience in blending public climate finance instruments with international carbon market mechanisms. Previous analyses (Fuessler et al., 2019; Spalding-Fecher et al., 2021) have explored "attribution", i.e., the allocation of mitigation outcomes, resulting from a program supported by both international climate finance and compliance carbon markets (Article 6), to each of those financing sources. "International climate finance" refers to international public resources that cover the additional costs of low carbon and climate resilient investments, beyond what commercial financing could support in a business as usual scenario, and for which there are no transfers of certified mitigation outcomes. However, the concept can be extended to encompass any concessional financing from any source, that should receive some "credit" for its contribution to the total cost of abatement, as well as to the VCM. "Proportional attribution" means attributing emission reductions to financers in proportion to their financial contribution to the abatement costs of the mitigation activity. Attribution methods use "grant value equivalent" which considers the timing of the finance and potentially also other parameters such as risk absorbed by financiers. For example, a loan that provides upfront financing has a different value to the project proponents than carbon revenue received after implementation, which is addressed through discounting all cash flows to present value. Attribution analysis should focus mainly on financing streams that support implementation and investment, rather than the smaller funding for activities such as technical assistance and capacity building (Spalding-Fecher et al., 2021). As noted by Spalding-Fecher et al. (2021), without proportional attribution, there is a risk that climate finance will essentially subsidise the price of carbon credits (i.e., the price of the credits will be lower than the unit abatement cost of the mitigation intervention), undermining market efficiency and resulting in higher global emissions, thus violating the principle of environmental integrity. In the context of the present case study of Swedish BECCS, the simplest form of attribution would involve attributing the tonnes of CDR in direct proportion to the revenues from results-based payments from the Swedish state and revenue from selling carbon removal credits on the VCM. A more elaborate approach to attribution would entail consideration of grants received and any concessionary loans, and so on.

4.3 Corresponding adjustment

To operationalise attribution in the case of Swedish BECCS, the preferred option would be the enabling of corresponding adjustments on EU level because the EU has a joint nationally determined contribution (NDC). A corresponding adjustment in the context of Article 6 of the Paris Agreement refers to the requirement for parties involved in the authorisation and international transfer of Internationally Transferred Mitigation Outcomes (ITMO) to ensure that the collective ambition of their NDCs is not undermined. Applying a corresponding adjustment means that the host country where the mitigation project occurs does not count the mitigation towards its targets so that the buyer of ITMOs can claim the associated mitigation outcome uniquely towards its target, e.g., another country towards its national mitigation target or an actor towards a voluntary mitigation target, such as a corporate net-zero target. It is currently not possible to make a corresponding adjustment on the EU level and it is unknown when it will be possible, and especially when (if ever) it will be possible for individual member states to make a corresponding adjustment at EU level based on individual overachievements (Ahonen et al., 2023).

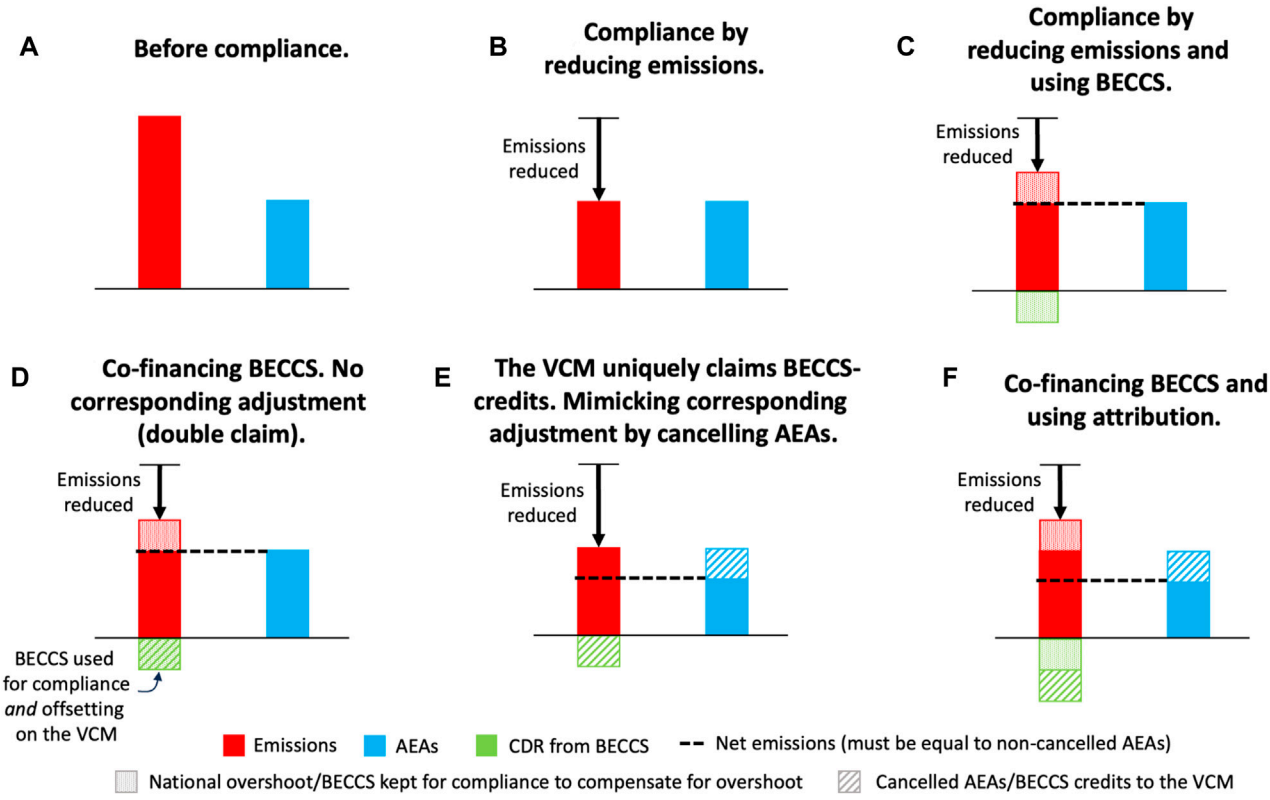


FIGURE 4
If CDR from BECCS is accounted for in the ESR, cancellation of AEAs can be a workaround until corresponding adjustments are enabled for EU member states. Panel **(A)** shows current emissions and the ESR emissions target for the member state, expressed as AEAs. In Panel **(B)**, emissions are reduced to a level equivalent to the allocated AEAs. In Panel **(C)**, a combination of emission reductions and CDR is used for compliance (net emissions equals allocated AEAs). Note that the emissions overshoot and the CDR to compensate for the overshoot is dotted, to emphasise that those are of equal size and correspond to each other. In Panel **(D)**, an amount of BECCS credits are sold to an actor on the VCM, without corresponding adjustment, for offsetting purposes, resulting in a double claim. In Panel **(E)**, double claiming is avoided since the member state cancels AEAs corresponding to the sold BECCS credits. Note that the cancelled AEAs and the BECCS credits are striped to show that those are of equal size and correspond to each other. In Panel **(F)**, half of the mitigation outcome is attributed to the VCM and half to the state, and AEAs are cancelled accordingly. As illustrated in **(E)** and **(F)**, the host country does not have to do less to comply with its mitigation target as a result of the international transfer, meaning that environmental integrity is maintained.

4.4 Alternative pathways until corresponding adjustments are enabled

Since the EU is yet to enable corresponding adjustments, we use this section to elaborate on other ways to adjust for exported BECCS outcomes in order to avoid double claiming of mitigation outcomes. The EU currently divides its emission accounting into three different sectors, namely, the EU Emissions Trading System (EU ETS), the Effort Sharing Regulation (ESR), and the Land Use, Land Use Change and Forestry (LULUCF) sector. It is currently unknown in which sector, EU ETS, ESR, LULUCF or a new sector, CDR from BECCS would be accounted for in the EU (Fridahl et al., 2023). In a communication to the European Commission, the Swedish government has expressed its wish to be able to use CDR from BECCS to compensate for emissions in the ESR sector (DN, 2023). To achieve the joint EU NDC, each member state is allocated some expected contribution in the ESR sector. This allocation is expressed in a certain number of annual emissions allocations (AEAs), which corresponds to a certain amount of emissions. Flexibility mechanisms allow for a member state that overachieves its target to sell the overachievement to another member state. Sweden has previously overachieved the target for the ESR sector, meaning that Sweden has had surplus AEAs. Interestingly, Sweden has historically, however, not proceeded to sell surplus AEAs but has instead cancelled them. This essentially increases the emission reduction requirement on the EU level, since it limits underachieving member states' opportunity to buy excess AEAs from overachievers. France and the UK have also cancelled AEAs (European Commission, 2020).

If CDR from BECCS were to be accounted for in the ESR sector, the cancellation of AEAs would offer a way for member states to mimic a corresponding adjustment without interfering with EU overall emissions accounting. Figure 4 illustrates how this could be done. Panel a) shows current emissions (in red) and the ESR emissions target for the member state, expressed as AEAs (in blue). Red bars can be interpreted as debts for the member state, while blue bars can be interpreted as assets. For compliance, emissions must be balanced by AEAs. In other words, red bars must be equal to the blue bars, or lower, which would constitute an overachievement. This can be achieved by reducing emissions to a level equivalent to the allocated AEAs, as shown in Panel b). If the amount of emission reductions is insufficient to reach the AEA level, CDR could be used to compensate for the overshoot, see Panel c), in which case net-

emissions (taken as emissions minus CDR, represented by the dotted line) equals the AEAs (represented by the blue bar). We have dotted the emissions overshoot and the needed CDR to compensate for the overshoot in order to reach compliance, to emphasise that those are of equal size and correspond to each other. Panel d) shows the situation where an amount of BECCS credits are sold to a non-state actor on the VCM, without corresponding adjustment, for offsetting purposes. The procedure in panel d) thus results in a double claim, since the credits are used by the purchasing actor for offsetting emissions while also contributing to compliance in the host country. Double claiming could be avoided if the member state cancels AEAs corresponding to the sold BECCS credits, see Panel e). Note that in e), where all BECCS mitigation outcomes are sold to the VCM, the BECCS outcome does not suffice for the host country to compensate for the overshoot after the cancellation of AEAs. We have striped the cancelled AEAs and the BECCS credits to show that those are of equal size and correspond to each other. If a BECCS-producer has produced a certain amount of CDR, from which half of the outcome is attributed to carbon credit revenues from the VCM and half to the revenue from the state support, transferring half of the outcome is possible if the state cancels AEAs corresponding to half of the produced BECCS outcome, see Panel f). As illustrated in e) and f), the host country does not have to do less to comply with its mitigation target as a result of the international transfer, meaning that environmental integrity is maintained. Note that in Panels c), d), and f), emission reductions are displaced to a certain level by carbon removal occurring concurrently. This represents so-called "mitigation deterrence" (more specifically "contemporaneous substitution" as defined by Bednar et al., 2023). Mitigation deterrence is an undesirable effect that may be induced if the option is introduced to use CDR from BECCS to comply with ESR targets. Mitigation deterrence is a real risk that would need to be addressed. The focus here, however, is to discuss on a principal level how double claims could be avoided. See Supplementary Material for a more comprehensive discussion about the mitigation deterrence risk.

The reasoning above is valid in the case where BECCS are placed in the ESR sector. But it may well be the case that BECCS are placed in the EU ETS, motivated by the fact that the facilities lie in the energy sector. Still, mimicking corresponding adjustment may be possible by individual member states by cancelling EU ETS allowances. In the EU ETS, each member state is allocated a certain number of EU ETS allowances, called EUAs, that are auctioned to industry. This allows for the member state to do a mimic corresponding adjustment by cancelling EUAs (rather than auctioning them) corresponding to exported BECCS credits.

5 Actionable recommendations

The present case study is an example of the interaction between public results-based finance and VCM finance for BECCS. According to the analysis presented in this paper, allowing double claiming of mitigation outcomes has disadvantages. Double claiming casts doubt upon the legitimacy of offsetting claims made by actors using carbon credits. Historically, offsetting claims based on the voluntary use of carbon credits have been based on the premise that offsetting entities can report lower GHG emissions than their actual carbon footprint because their use of the carbon credits have caused GHG emissions to be reduced elsewhere only due to the incentives created by the carbon credits used. When double claiming is allowed, the same mitigation outcome can be counted towards an existing national mitigation target and the mitigation target of a company that uses carbon credits for offsetting. In this situation, the most tangible impact of the offsetting entity's use of carbon credits may be to help the host country of the mitigation activity from which the carbon credits were issued to save expenditures for meeting its already pledged mitigation ambition. The latter situation is arguably a less convincing case for the offsetting entity to report lower GHG emissions than their actual carbon footprint (Kreibich and Hermwille, 2021; Ahonen et al., 2023). Another problem is that, as this paper has shown, without proportional attribution in case of co-financed projects, public funding effectively subsidises the carbon credit price faced by the carbon market. This might lead to lowering the ICP set voluntarily by actors, which in turn can lead to decreased decarbonisation efforts and result in a higher residual emission level. This latter effect has, to the authors' knowledge, not previously been discussed in the literature that covers the interaction between public funding and VCM revenue in mobilising capital for mitigation activities.

Based on the case study it is recommended that:

The double claiming of mitigation outcomes towards existing national mitigation targets and voluntary offsetting targets should be disallowed through the introduction of regulation at relevant levels, e.g., national legislation and by international standard setting bodies.

Proportional attribution should be applied in situations where results-based payments for mitigation outcomes used towards national mitigation targets are combined with VCM finance. Spalding-Fecher et al. (2021) proposed that an important role of crediting standards could be to develop principles for proportional attribution, to be implemented in the certification of carbon credits. The significance of that recommendation is confirmed by the present study.

Corresponding adjustments should, if possible, be carried out on the basis of the outcome of attribution analysis, to avoid the disadvantages attached to double claims identified through this study.

As this paper has described, EU member states currently lack the ability to perform corresponding adjustments. It is recommended that governments work towards enabling corresponding adjustments by exploring what changes and updates to legislation would be required on the national level in EU member states, and on EU level.

There may be alternatives to corresponding adjustments that can avoid the identified disadvantages attached to double claiming, as this paper has exemplified. EU member states that wish to facilitate the contribution of the VCM to GHG mitigation in their jurisdictions with high-integrity outcomes are recommended to explore alternative pathways to corresponding adjustments until corresponding adjustments are enabled.

6 Discussion

The present case study has considered co-financing of BECCS by state support and VCM revenue. The vast capital required to close the CDR financing gap, and for low-carbon investments in general, to enable meeting the Paris Agreement temperature target creates a situation where combining multiple streams of financial support is

likely to become more common by necessity. We have demonstrated how double claiming of mitigation outcomes can cause problems related to the environmental integrity of the voluntary use of carbon credits towards offsetting claims. Our recommendations might have positive or negative impacts on the BECCS deployment. Proponents of allowing double claiming of co-financed BECCS (and thus the subsidisation of BECCS credits) could argue that BECCS credits would be too expensive to be interesting for actors on the VCM if they must bear the entire cost themselves, and that this would decrease the interest in buying BECCS credits, thus resulting in less BECCS (Möllersten and Zetterberg, 2023). Conversely, we see a possibility for higher BECCS deployment if governments take full responsibility to achieve their set-out climate targets, without counting on contributions from the VCM to co-finance BECCS, since waiting for the VCM to step in to incentivise BECCS could lead to postponing national policies promoting BECCS. In other words, there may be a risk of postponing policy due to (over-)reliance on the VCM in the case of expecting co-financing, which could lead to less BECCS deployment. Furthermore, in a scenario without double claiming, VCM support towards BECCS would lead to BECCS deployment in addition to that deployed due to national policies, thus raising ambition beyond existing national mitigation targets. Another argument as to why our recommended attributions-approach and avoiding double claiming might result in more BECCS is that the VCM rely on trust among market actors, the public, and other stakeholders, and accusations of lacking environmental integrity, e.g., greenwashing accusations, reduce the appetite among actors to participate in the markets. Recent legislative developments in the EU even include the prohibition of offsetting claims in business-to-consumer situations, largely motivated as a way to protect consumers from misleading claims and to prevent greenwashing (European Parliament, 2024). Safeguarding environmental integrity will therefore arguably be important to build confidence in the VCM to enable the utilisation of its potential to mobilise investment.

Although the present case study concerns the interaction between public results-based finance and VCM finance for BECCS, the relevance of the results extend beyond the context of the case study. The integrity problem associated with offsetting claims when double claiming occurs is relevant regardless of the mitigation technology or method involved (e.g., Kreibich and Hermwille, 2021; Ahonen et al., 2022). Problems related to the subsidisation of the price of carbon credits are not limited to BECCS project activities. They are, moreover, also relevant for situations that involve compliance carbon markets rather than the VCM (Spalding-Fecher et al., 2021) and, plausibly, situations in which the mitigation outcome is not counted towards national mitigation targets.

One caveat of this study that should be mentioned is that it has shown on a principal level that there are mechanisms by which the subsidisation of carbon credits may reduce non-state actors' voluntary decarbonisation efforts. However, the importance of the identified mechanisms remains to be further evaluated including quantitatively assessing their impact. Nonetheless, the combination of actors setting mitigation targets voluntarily, to be met in part by offsetting, especially as net-zero targets, and the increasing call by scholars and standard-setters influencing such actors and targets to offset emissions by using CDR credits in the context of net-zero targets, makes CDR carbon credit prices particularly likely to have an impact on voluntary GHG mitigation strategies.

We suggest the application of attribution, accompanied by corresponding adjustments or equivalent procedures. Since corresponding adjustments are yet to be enabled on the EU-level, we also suggest possible workarounds which would equate to a corresponding adjustment in the meantime. It is currently unknown when, or even if, member states will be able to operationalise corresponding adjustments since they have to be made on EU-level due to the joint nature of the EU NDC. The first Swedish BECCS projects, which will likely be co-financed by the planned state reverse auctions and VCM revenue, can be expected to be implemented roughly by 2027 if auctions are held in 2024 as planned. By then, developments might have occurred that enable corresponding adjustments, but there are large uncertainties. Notably, a pilot project by the Swedish and Swiss governments to investigate the operationalisation of Article 6.2 of the Paris Agreement for CDR was announced in November 2023 (Swedish Energy Agency, 2023). The project might contribute to bringing clarity concerning how Sweden could make corresponding adjustments for BECCS outcomes. Furthermore, EU-level developments can be expected for corresponding adjustments since the EU ETS is being linked to the Swiss emission trading system (Dutch Emissions Authority, 2024), which means that corresponding adjustments might be needed between Switzerland and the EU. However, enabling corresponding adjustments between the EU and Switzerland for this specific case might not enable corresponding adjustments for other cases, such as the case for individual member state overachievement sold to the VCM.

This analysis has shown that proportional attribution can make important contributions to prevent undesired outcomes when projects are co-financed through public and VCM finance. Spalding-Fecher et al. (2021) have shown, considering the combined concessionary international climate finance and finance from compliance carbon markets (Article 6), that unless proportional attribution is implemented, there is a risk that efficiency of markets is undermined, and that global emissions will end up higher, thus violating the principle of environmental integrity. Due to the limited experience in blending public and carbon credit market finance (compliance as well as VCM), and of proportional attribution in particular, more work is required to raise awareness and readiness among key actors in public and carbon credit markets, agree on principles for attribution, and develop support tools, etc., to enable the application of attribution principles in scaled-up mitigation cooperation (Spalding-Fecher et al., 2021). Extensive future research is also needed to fully understand the environmental integrity implications of blending public and carbon credit market finance.

Author contributions

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Conflict of interest

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2024.1387138/full#supplementary-material

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The digital transformation, funding constraints, and the green innovation of transportation companies

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Facing increasingly pressing environmental issues, driving green transformation through innovation has become a necessary path for the future development of companies. Empirical analysis based on the sample of listed companies in the transportation sector in China from 2011 to 2021 reveals that digital transformation in transportation companies can promote green innovation. Furthermore, the impact of digital transformation on green innovation is sustained, with the lagged effect of digital transformation having a greater influence on green innovation than the current effect. The study also discovers the presence of a mediating effect of financing constraints between digital transformation and green innovation. Further research, using the promulgation of the *Digital Transportation Development Plan Outline* in 2017 as a quasi-natural experiment, employs the difference-in-differences method to verify the impact of the policy on green innovation in transportation companies before and after its implementation. The results demonstrate the introduction of digital policies contributes to promoting green innovation in companies. Economic consequences research suggests that green innovation can effectively reduce carbon emissions intensity. With the goal of the "carbon peaking and carbon neutrality" strategy, actively promoting the integration of digitalization and green innovation is crucial for enhancing the sustainable development of transportation companies.

KEYWORDS

transportation, digital transformation, green innovation, financing constraints, carbon emissions

1 Introduction

China's economy is experiencing rapid development, yet our environmental conditions are facing serious challenges. Creating a sustainable development environment is a significant test we face in the future. With the advent of a new wave of technological revolution and industrial transformation, green innovation technology has become the motivation companies to transform their economic development methods and achieve sustainability.

Building a country with a strong transportation network is a pioneer field in building a modernized economic system. As a key foundational sector for economic and social prosperity and stability, the transportation industry plays a vital role in China's economic development. However, with population growth and the process of industrialization, the transportation sector has become one of the four major carbon-

emitting industries in our country, exerting significant pressure on carbon emissions (Uhere et al., 2010). China has explicitly proposed the goal of "carbon peaking" by 2030 and "carbon neutrality" by 2060, and it is the long-term responsibility of companies to achieve the "dual carbon" goals. At present, carbon emissions from transportation remain on a growing trend, technological level and energy structure of transportation development have not been fundamentally transformed, so the situation of carbon emission reduction in the transportation field is grim. "Green and low-carbon transportation actions" has been listed as a separate chapter in the *Notice on the Action Plan for Peaking Carbon Emissions Before 2030* that issued by the State Council. *The Green Transportation Development Plan for the 14th Five-Year Period* issued by the Ministry of Transport clearly mentioned that continuously promoting green science and technology innovation, accelerating technological research and development and its application promotion, and forming a new pattern of green transportation development. It can be seen that the green transformation of transportation companies is the key to future development.

With the development momentum of global digitalization, digital economy has grown rapidly in recent years, the average score of Digital Economy Development Index (TIMG) increased by 26% from 45.33 in 2013 to 57.01 in 2021. It is increasingly evident that major countries catch-up with each other in digital economy, the median of global TIMG Index has begun to exceed the global average level and shows an accelerating upward trend. In particular, score of China's Digital Economy Development Index (TIMG) increased by 28% from 63.43 in 2013 to 81.42 in 2021, the digital economy is gradually becoming an important driving force of China's high-quality economic and social development. The rapid development of the digital economy has become crucial for enhancing the core competitiveness of businesses. With the successive release of documents such as the *China Digital Economy Development White Paper*, the *Notice on Accelerating the Digital Transformation of State-Owned companies*, and the *14th Five-Year Plan for Digital Transportation*, it has become an inevitable trend for the transportation industry to transform its operations through digitalization, aiming to improve efficiency, reduce costs, enhance customer experiences, and innovate business models. Simultaneously, the deep integration of digital technology and transportation companies facilitates the achievement of comprehensive, environmentally-friendly, and low-carbon transportation development. Therefore, clarifying the impact of digital transformation on green innovation in transportation companies can provide theoretical guidance for their sustainable development.

The advent of digital technology has brought about changes in the overall business environment. Existing literatures analyze the antecedents, outcomes, and other aspects of digital transformation (Henfridsson et al., 2014), where the outcomes of digital transformation contain new company products, company performances, company innovations and many other dimensions. By discussing companies improve the operational quality and efficiency of companies through digitalization, scholars opined that digital transformation can bring companies with new products, services, and skills, and then summarized that the digitalization of companies boosting the competitiveness of companies, improving the innovation of companies, etc. (Mergel et al., 2019). Scholars have also explored the impact of different digital technologies such as big data (Ghasemaghaei and Calic, 2020) and the Internet (Glavas and Mathews, 2014) on companies' technological innovation, the outcomes of the studies find that digital technologies can promote innovation level of companies. With the enhancement of company digital transformation and severe environmental issues, the impact of digital transformation on companies' green innovation has gradually become a hot topic of academic attention.

Scholars have discussed the impact of digital technology on green transformation in companies and have identified new opportunities that arise from its emergence (Ahmad et al., 2022; Zhu et al., 2023). Studies conducted by Mubarak et al. (2021) and Luo et al. (2022) all acknowledge that digital technology can propel green transformation in companies, but the mechanisms through which this impact is achieved differ. The former suggests that digital technology enhances information dissemination and knowledge accumulation, thereby promoting green innovation activities within companies. On the other hand, the latter argues that the openness, inclusivity, and mobility inherent in digital technology can effectively address the cost and technological challenges faced during green transformation. However, some scholars also highlight the heterogeneity in the role of digitization in driving green transformation across industries and regions (Li and Shen, 2021; Gao et al., 2023). Peng et al. (2022) stated that the impact of digitalization on company green transformation shows "inhibitory effect" first, then "facilitate". Thus, a consensus has yet to be reached regarding the magnitude and mechanisms through which digital transformation influences green innovation in companies. Consequently, what is the relationship between the digital transformation of transportation companies and green innovation? How does digital transformation drive green innovation in these companies?

The present study focuses on the sustainable development of transportation companies, specifically examining the green innovation pathways driven by digital transformation in the transportation industry. Recognizing that funding is vital to the survival of companies, transportation companies face significant pressure in securing diverse sources of capital. Attracting social capital investment has been a persistent challenge for these entities. In light of these considerations, this study explores the following aspects in conjunction with the unique characteristics of transportation companies: firstly, it analyzes the static and dynamic impacts of digital transformation on green innovation in transportation companies; secondly, it investigates how digital transformation can drive green transformation from perspective of financial constraint; thirdly, it reveals the influence of digital policies on green innovation in companies and the economic consequences resulting from green innovation in transportation companies. This research provides a theoretical foundation for the green transformation of transportation companies and contributes to the exploration of digital policies that can further facilitate

environmentally-friendly development by offering insights for establishing a supportive framework for digital reforms.

2 Literature review

2.1 Research on green innovation

Environmental issues generated in the process of economic development, such as environmental pollution, scarcity of resources have gradually become significant influencing factors that restrain economic development of China (Bai et al., 2015). Therefore, the shift to resource conservation and improve resource utilization efficiency is a must for sustainable economic development (Bai et al., 2014). However, green transformation of economy need to put micro companies into practice, the development of green innovation in companies is a key factor to achieve green transformation economy or not. James (1997) defined green innovation as the introduction of new processes or products that significantly reduce environmental impact while adding value to individuals or businesses. In comparison to conventional technological innovation, green innovation not only retains characteristics such as long innovation cycles, large investment scale, high risks, strong uncertainty, and substantial adjustment costs, but also requires improving the efficiency of resource and energy usage and reducing the environmental costs associated with raw material consumption (Chen, 2008; Takalo and Tooranloo, 2021). Factors that affecting the green transformation of companies have also gradually become the focus of scholars' attention.

In terms of internal influencing factors of companies, green product innovations can help to promote the image and reputation of companies, it can also help companies to improve overall competitiveness (Liao, 2018a). Meanwhile, green innovation help companies to reduce polluting production methods, bring company environmentally friendly production technology, promote the utilization efficiency of resources, and thus improve business operation efficiency (Jansson, 2013; Liang et al., 2020). From the view of external influencing factors of companies, firstly, government supervision and stringent environmental laws and regulations are the important driving forces of companies' green transformation (Johnstone, 2010), which enforce companies on improving standards of green innovation. Secondly, in order to evade environmental risk, banks make loan decisions based on companies' environmental information, and reduce the amount of loans to companies with poor environmental performance, therefore, companies promote their levels of green innovation to access green credits from banks (Thompson and Cowton, 2004; Liu et al., 2010; Nandy and Lodh, 2012). Lastly, clients, investors, and other stakeholders will impact the green transformation of companies as well, companies obtain more competitive advantages through green innovation, and media evaluation will also have a certain supervision effect on the green development of companies (Jiguang and Zhiqun, 2010; Huang et al., 2016; Liao, 2018b; Abbas and Sağsan, 2019).

Obviously, there are many factors affect green innovation of companies, and it is different from traditional innovation, which has higher requirements on knowledge spillover rate, capital demand, sustainability, and how to improve efficiency of resource acquisition and allocation is the key to companies' green innovation.

2.2 Research on digital transformation

Digital transformation is an application of new technology to companies, such as Artificial Intelligence, Big Data, and cloud computing, use these new information technologies to empower overall management and production of companies. The goal of digital transformation is to enhance companies' core competitiveness, and change the way of value creation to achieve value growth, improve the quality of information supply and conduction efficiency through higher efficient flow of information, reorganize and optimize resources of production to achieve major business improvements (Kuusisto, 2017; Dornberger, 2018).

Existing research confirms that digital transformation can improve efficiency of company resources allocation, promote input-output efficiency of companies (Graetz and Michaels, 2018; Levine and Warusawitharana, 2021). Digital transformation can also help to improve companies' ability to obtain external resources and information research capabilities, which help companies deliver positive signals to the outside world while reducing the level of information asymmetry between internal and external investors. As the study progressed, scholars explore influences of digital transformation on companies' operational models, financing cost, level of company governance and innovation, etc. In the context of green transformation strategy, the question of whether digital transformation affects the green innovation of companies has also gradually become the focus of academic attention.

3 Research hypotheses

3.1 Digital transformation and corporate green innovation

Compared to traditional innovation activities, green innovation combines dual attributes of both environmental protection and innovation. The innovation investment of companies requires a large amount of resources, how to obtain and coordinate a large amount of external resources effectively is the key to the innovation investment of companies. By leveraging digital technology, companies can enhance their ability to acquire resources and integrate internal and external knowledge (Gobble, 2018). They can also use low-cost digital transactions to broaden the knowledge supply required for technological innovation (Björkdahl, 2020; Wen et al., 2022; Maretto et al., 2023), thus enhancing their advantages in technological innovation. At the same time, digital transformation can accelerate the penetration of knowledge information, effectively reduce the trial-and-error costs of innovation, and reduce the huge costs associated with innovation. Therefore, both in terms of knowledge spillovers and costs, digital transformation can enhance corporate innovation. From perspective of environmental protection, digital transformation enhances companies' ability to acquire and allocate resources efficiently,

which help company to grasp the development trend, concept and technology of green innovation, and providing support (Strambach, 2017; Arias-Pérez et al., 2021). Furthermore, digital transformation also promotes the iteration and renewal of digital technologies, enabling the synergy between foundational digital technologies and specific technologies, thereby generating technological spill-over effects that promote corporate green innovation (Yang et al., 2022; Wang and Yan, 2023).

Transportation companies sustain significant environmental, market competition, and safety risks. Continuously enhancing technological advancement is an essential requirement for these companies to adapt to socioeconomic development. Based on social responsibility, digital transformation is essentially mathematical thinking that involves openness, co-creative and sharing, it strengthen the willingness of companies to fulfill social responsibilities by including more community of shared interest in decision-making. Transportation companies achieve carbon reduction, pollution reduction, and improve energy utilization efficiency through green innovation, which is a vital pathway to fulfill companies' social responsibility, it can be seen that digital transformation can help to boost motivation of companies green innovation. Drawing upon institutional theory, transportation companies face regulatory pressures from governments and competitors (Okereke and Russel, 2010). The application of new technologies can help reduce energy consumption and address noise and dust issues (German et al., 2023).

Therefore, transportation companies need to continuously improve their level of green innovation. Through the information transmission and knowledge integration facilitated by digital transformation, companies can promote green innovation. Moreover, digital transformation is a comprehensive endeavor and a long-term task. Similarly, green innovation is a continuous and gradually accumulated process. Hence, both the current and lagged digital transformations of companies have an impact on green innovation. Based on this point of view, this study proposes the following hypotheses:

H1a: There is a positive correlation between digital transformation of transportation companies and their current level of green innovation.

H1b: There is a positive correlation between digital transformation of transportation companies and their future level of green innovation.

3.2 Digital transformation, financing constraints and green innovation

The process of green innovation cannot be achieved without adequate financial support. Previous research has highlighted that financial constraints remain a significant factor limiting innovation activities in businesses (Czarnitzki and Hottenrott, 2010; Milani and Neumann, 2022). As representatives of cyclical industries, transportation companies are particularly vulnerable to economic fluctuations (Drobetz et al., 2016). Under the influence of COVID-19 pandemic, global economic issue has further exacerbated the financial constraints faced by transportation companies. Additionally, as capital-intensive industries, transportation companies heavily rely on substantial investments in transportation equipment, roadways, air and sea routes, and railway lines. Consequently, a decrease in transportation volume has a significant impact on their revenue (Ngo, 2019). Thus, the financial challenges confronted by transportation companies during the process of green innovation not only involve securing external financing but also internal cash flow vulnerability, which is susceptible to operational conditions. Therefore, addressing the issue of stable financial constraints and ensuring sufficient funding is crucial to facilitating green innovation in these companies.

Digital transformation can alleviate financing constraints for companies in two aspects. Firstly, the processes of information transmission, data collection, and analysis in digital transformation enable companies to leverage vast amounts of information at lower costs. By utilizing information technology tools to filter market information, companies can address the issue of information asymmetry between fund suppliers and demanders, thus mitigating financing constraints (Peng and Tao, 2022; Chen and Xu, 2023). Secondly, digital transformation accelerates the transmission and integration of information among different organizational units within the company. This facilitates communication, effective supervision, and feedback regarding the utilization and allocation of internal funds, thereby reducing the risks associated with imbalanced internal capital allocation and promoting green innovation (Behera, 2021; Kostakis and Kargas, 2021).

In conclusion, digital transformation helps companies reduce financing costs, enhance internal information analysis, mitigate risk expectations, and alleviate financing constraints. This, in turn, prevents reductions in green innovation investments caused by insufficient funds. Based on these points, the following hypothesis is proposed in this study:

H2: Digital transformation stimulates green innovation in transportation companies by alleviating financing constraints.

4 Research design

4.1 Data source and sample selection

Due to the significant impact of the COVID-19 pandemic on domestic transportation industry in 2022, the operational revenue and net profit of transportation companies have been greatly affected. To mitigate the influence of the pandemic, this study focused on the Shanghai and Shenzhen listed transportation companies from 2011 to 2021. All continuous variables were subjected to a winsorization technique, trimming the extreme values at the upper and lower 1% tails. Additionally, samples that were classified as ST, *ST, and those with missing key variables were excluded, resulting in a final dataset comprising 769 annual observations.

4.2 Variable definitions

4.2.1 Dependent variable: green technological innovation (*GREEN*)

The patent types include invention, utility model, and design patents. Following the approach of Song et al. (2022), this study

adopted the IPC codes identified in the *Green Patent Inventory* published by the World Intellectual Property Organization (WIPO) to define green innovation, including both invention and utility model patents. To avoid the influence of zero values, the level of green innovation in companies (*PTI)* was measured by taking the logarithm of the sum of green invention patents and utility model patents, with an additional 1 added. For robustness checks, the proportion of green patent applications by companies (*EPR*) was also utilized, which represents the ratio of green patent applications to total patent applications in a given year.

$$PTI = \ln(1 + \text{number of green invention patents} + \text{number of utility model patents}) \quad (1)$$

$$EnvrPatRatio = \text{number of green patent applications} / \text{total number of patent applications} \quad (2)$$

4.2.2 Independent variable: digital transformation (*DCG*)

This study utilized Python web scraping techniques to extract textual information from the annual reports of transportation listed companies. Based on predefined keywords, the texts were searched, matched, and word frequencies were counted. The frequencies were then categorized, aggregated, and digitally processed to derive relevant indicators of corporate digital transformation. The keywords include artificial intelligence technology, big data technology, cloud computing technology, blockchain technology, and digital application technology.

4.2.3 Mediating variable: financial constraints (*KZ*)

Building upon the research of Kaplan and Zingales (1997), this study constructed a financial constraint index based on various financial indicators such as operating net cash flow, dividends, cash holdings, leverage ratio, and Tobin's Q. The specific steps include: (1) categorizing the operating net cash flow/previous total assets (CF_{it}/A_{it-1}), cash dividends/previous total assets (DIV_{it}/A_{it-1}), cash holdings/previous total assets (C_{it}/A_{it-1}), leverage ratio (LEV_{it}), and Tobin's Q (Q_{it}) based on whether their values are below or above the median. If the value of CF_{it}/A_{it-1} is below the median, KZ_1 is assigned a score of 1; otherwise, it is assigned a score of 0. If the value of DIV_{it}/A_{it-1} is below the median, KZ_2 is assigned a score of 1; otherwise, it is assigned a score of 0. If the value of C_{it}/A_{it-1} is below the median, KZ_3 is assigned a score of 1; otherwise, it is assigned a score of 0. If the value of LEV_{it} is above the median, KZ_4 is assigned a score of 1; otherwise, it is assigned a score of 0. If the value of Q_{it} is above the median, KZ_5 is assigned a score of 1; otherwise, it is assigned a score of 0. (2) Calculating the KZ value,

$$KZ = KZ_1 + KZ_2 + KZ_3 + KZ_4 + KZ_5. \quad (3)$$

Estimating the regression coefficients of the variables by establishing a regression model

$$KZ = \frac{\alpha CF_{it}}{A_{it-1}} + \frac{\beta DIV_{it}}{A_{it-1}} + \frac{\gamma C_{it}}{A_{it-1}} + \delta LEV_{it} + \varepsilon Q_{it} + \epsilon. \quad (4)$$

Utilizing the results from the regression model, the KZ index can be calculated. A higher KZ value indicates a higher level of financial constraints for the company.

The WW and SA index is also used as a proxy variable for financing constraints for robustness test (Whited and Wu, 2006; Hadlock and Pierce, 2010).

$$WW = -0.091*CF - 0.062*DIVPOS + 0.021*TLTD - 0.044*SIZE + 0.012*IGROWTH - 0.0035*GROWTH. \quad (5)$$

Where *CF* is the ratio of cash flow to total assets; *DIVPOS* is a dummy variable for dividend payment; *TLTD* is the ratio of long-term liabilities to assets; *SIZE* is the natural logarithm of total assets; *IGROWTH* represents the growth rate of revenue in the industry where the company is located; and *GROWTH* is the growth rate of the company's revenue. The *WW* index varies in the same direction as the corporate financing constraint, for instance, the larger the value of WW, the higher degree of the company financing constrained.

$$SA = -0.737*SIZE + 0.043*SIZE^2 - 0.04*AGE. \quad (6)$$

Where *SIZE* is the natural logarithm of total assets; *AGE* represents the company age.

4.2.4 Control variables

This study controlled for the following variables: company size (*SIZE*), leverage ratio (*LEV*), ownership concentration of the largest shareholder (*EQUITY*), revenue growth rate (*GROWTH*), proportion of fixed assets (*PPE*), company age (*AGE*), and annual variables (*YEAR*). Additionally, considering the influence of regional economy on company digitization, the companies were categorized into Eastern, Western, and Central regions, and dummy variables (*AREA*) were introduced to account for the regional effect. Furthermore, taking into account the temporal nature of company's green innovation activities, the control variables were lagged by one period.

4.3 Model specification

To test the hypotheses of this study, models (7) and (8) were constructed to examine the impact of digital transformation on company's green innovation and its underlying mechanisms.

$$GREEN_{i,t} = \alpha_0 + \alpha_1 DCG_{i,t} + \alpha_2 Control_{i,t} + \alpha_3 YEAR_i + \varepsilon \quad (7)$$

$$KZ_{i,t} = \beta_0 + \beta_1 DCG_{i,t} + \beta_2 Control_{i,t} + \beta_3 YEAR_i + \varepsilon \quad (8)$$

5 Empirical testing and analysis

5.1 Descriptive statistics

Table 1 presents the descriptive statistics of the main variables. The results indicate that the mean value of the dependent variable, green innovation (*PTI*), is 0.573, with a maximum value of 4.836 and a minimum value of 0.000. As for *EPR*, the mean value is 0.172, with a maximum of 1.000 and a minimum of 0. These values suggest a relatively low level of participation in green innovation activities among the transportation companies. The mean value of the explanatory variable, digital transformation (*DCG*), is 1.019, with a maximum value of 4.700 and a minimum value of 0, indicating a significant variation in the degree of digital transformation among

TABLE 1 Descriptive statistics of the main variables.

Variables	Mean	Standard deviation	Minimum	Median	Maximum
PTI	0.573	0.888	0.000	0.000	4.836
EPR	0.172	0.073	0.000	0.000	1.000
DCG	1.019	0.942	0.000	1.098	4.700
KZ	1.429	1.205	−3.406	1.354	9.822

TABLE 2 Regression results.

Variables	(1)	(2)	(3)
	DCG	DCGt-1	DCGt-2
DCG	0.086** (2.26)	0.091** (2.31)	0.105*** (2.64)
SIZE	0.302*** (10.87)	0.306*** (11.04)	0.307*** (11.07)
GROWTH	0.089 (1.41)	0.103 (1.64)	0.132** (2.02)
LEV	−1.090*** (−4.64)	−1.070*** (−4.57)	−1.108*** (−4.74)
EQUITY	0.007*** (2.63)	0.007** (2.58)	0.007*** (2.72)
PPE	−0.799*** (−4.90)	−0.821*** (−5.00)	−0.810*** (−4.92)
AGE	0.009 (1.54)	0.008 (1.49)	0.009* (1.66)
YEAR	Controlled	Controlled	Controlled
AREA	Controlled	Controlled	Controlled
Constant	−6.232*** (−10.04)	−6.310*** (−10.26)	−6.377*** (−10.31)
F	25.15	26.05	26.39
Adj R^2	0.272	0.277	0.280

***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

TABLE 3 Regression results of mechanism test.

Variables	(1)	(2)	(3)
	DCG	DCGt-1	DCGt-2
DCG	−0.082* (−1.79)	−0.088* (−1.88)	−0.075* (−1.69)
SIZE	−0.240*** (−7.21)	−0.237*** (−7.18)	−0.237*** (−7.25)
GROWTH	0.054 (0.72)	0.072 (0.97)	0.041 (0.53)
LEV	4.808*** (17.07)	4.742*** (17.02)	4.707*** (17.16)
EQUITY	−0.001 (−0.16)	−0.006 (−0.97)	−0.001 (−0.29)
PPE	−0.065 (−0.34)	−0.072 (−0.37)	−0.061 (−0.32)
AGE	−0.001 (0.10)	−0.001 (0.12)	−0.001 (0.15)
Year	Controlled	Controlled	Controlled
Area	Controlled	Controlled	Controlled
Constant	4.870*** (6.55)	4.889*** (6.68)	4.891*** (6.75)
F	53.65	54.15	52.34
Adj R^2	0.449	0.448	0.442

***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

transportation companies. Furthermore, the maximum value of the mediating variable, financial constraint (*KZ*), is 9.822, with a mean value of 1.429, indicating that transportation companies face severe financial constraints.

5.2 Analysis of benchmark regression results

A multiple regression analysis was performed using Model (7) to examine the relationship between digital transformation and green innovation in transportation companies. The results, presented in Table 2, column (1), reveal a significant positive correlation between *DCG* and *PTI*, indicating that digital transformation in transportation companies contributes to the enhancement of their green technological innovation level. Economically speaking, for each increase of one standard deviation in digital transformation, green innovation in companies will increase by 0.091 standard deviations. Thus, hypothesis H1a is validated.

Analysis of the benchmark regression model considered the timeliness of green innovation in companies. To further examine the dynamic effects of digital transformation, *DCG* was lagged by one period and two periods respectively, and the validation was conducted again using Model (7), as shown in Table 2, columns (2) and (3). The results reveal that DCG_{t-1} and DCG_{t-2} are both significantly positively correlated with *PTI*, and the coefficients of the lagged periods are larger than the current period coefficient. Hence, hypothesis H1b is validated. Economically speaking, for each increase of one standard deviation in digital transformation, green innovation in companies increases by 0.097 and 0.111 respectively. It is evident that the impact of digital transformation on green innovation has timeliness, with the lagged periods of digital transformation having a more significant influence. This study suggests that digital transformation is not a short-term project that can be achieved instantaneously. Instead, it is a long-term process that requires gradual and sequential changes. Throughout this process, it is crucial to continuously improve efficiency, reduce

TABLE 4 Substitution variable test.

Variables	ERP	WW	SA
DCG	0.049** (2.02)	−0.050* (−1.96)	−0.050*** (−4.68)
Control	Controlled	Controlled	Controlled
YEAR	Controlled	Controlled	Controlled
AREA	Controlled	Controlled	Controlled
Constant	−4.383*** (−11.23)	4.430*** (11.19)	6.113*** (3.29)
F	24.28	24.30	26.74
Adj R^2	0.210	0.211	0.221

***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

costs, and enhance the company's ability to acquire resources. Additionally, the integration of knowledge required for innovation also needs to be constantly accumulated. Therefore, there is a corresponding lag in the impact of digital transformation on green innovation.

6 Mechanism testing

Model (8) was used to test the mediating effect of financing constraints. The coefficients of *DCG* in columns (1), (2), and (3) of Table 3 are significantly negative. In economic terms, the impact of digital transformation on financing constraints varies in different years. Specifically, for each standard deviation increase in digital transformation in the current period, financing constraints decrease by 0.064 standard deviations. Lagging digital transformation by one period leads to a decrease in financing constraints by 0.069 standard deviations, while lagging it by two periods only results in a decrease of 0.059 standard deviations in financing constraints. It can be observed that the impact of digital transformation on financing constraints is most significant when lagged by one period and least significant when lagged by two periods. This indicates that digital transformation effectively addresses information transmission issues and helps businesses access internal and external information. The impact of digital transformation on financing constraints is relatively "timely". Showing that digital transformation reduces the companies' financing constraints, facilitates their green innovation investments.

7 Robustness testing

7.1 Substitution variables

To test the robustness of the mediating effect of funding constraints on the relationship between the digital transformation and the green innovation and enhance the credibility of this study we conduct the following robustness test. The research replaces the variable of company technological innovation and the variable of funding constraints into the proportion of green patent applications (EPR)、 WW index and SA index. The results, as shown in Table 4, continue to support the previous conclusions.

TABLE 5 Instrumental variable test.

Variables	(1)	(2)
DCG	0.077*** (6.88)	0.020* (2.79)
Control	Controlled	Controlled
YEAR	Controlled	Controlled
AREA	Controlled	Controlled
Adj R^2	0.540	0.250

***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

7.2 Instrumental variable method

Instrumental variables were selected appropriately for the core explanatory variables to address endogeneity issues. Total volume of post and telecommunication operations are used as the instrumental variable, to analyses using two stage least square, Table 5 states the results. As shown in Table 5, after consideration of endogeneity, the effect of digital transformation on improving green innovation in companies holds still, results were significant at 1% level.

7.3 Company ownership heterogeneity analysis

The previous empirical analysis has controlled for region, year, and to further verify the reliability of the results, companies were categorized according to the nature of their ownership, the results shown in Table 6, the results still support the previous conclusions, moreover, compared to state-owned enterprises, the digital transformation of non-state-owned enterprises promote the level of green innovation more effectively.

8 Further analysis

8.1 Study on the role of policy promotion

With the issuance of the *Outline of the Construction of a Strong Transportation Country* and the *Outline of the National Comprehensive Stereoscopic Transportation Network Plan*, the construction of an integrated, digitalized, and green modern comprehensive transportation system has become the goal of the transportation industry's development. In 2017, the Ministry of Transport issued the *Outline of the Development Plan for Digital Transportation*, which emphasizes the development of digital transportation as a goal, supports the construction of a strong transportation country, and proposes "multi-channel fundraising and exploration of government and social capital cooperation models". The purpose of this outline is to facilitate innovation as the primary motivation for transport development, to promote the deep integration of advanced information technology and transportation, take "data chain" as a main line to build digital collection system, networked transmission system and intelligent application system, accelerating transformation to digitization, networking, intelligence. The outline specifically indicates that digital

TABLE 6 Company ownership heterogeneity test.

Variables	State-owned Enterprises		Non-state-owned Enterprises	
	GREEN	KZ	GREEN	KZ
DCG	0.103** (2.35)	−0.063** (−2.01)	0.192*** (4.17)	−0.093* (−1.87)
Control	Controlled	Controlled	Controlled	Controlled
YEAR	Controlled	Controlled	Controlled	Controlled
AREA	Controlled	Controlled	Controlled	Controlled
Constant	−3.718*** (−5.14)	3.909*** (3.95)	−7.023*** (−7.027)	6.227*** (3.22)
F	7.89	42.79	27.60	43.43
Adj R^2	0.110	0.396	0.382	0.513

***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

TABLE 7 Regression results of policy promotion.

Variables	PTI	EPR
DID	0.387*** (6.65)	0.211** (2.28)
Control	Controlled	Controlled
YEAR	Controlled	Controlled
AREA	Controlled	Controlled
Constant	−5.747*** (−12.10)	−4.206*** (−11.25)
F	33.91	24.88
Adj R^2	0.273	0.229

***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

TABLE 8 Regression results of economic consequences.

Variables	*CR*	*CR*
PTI	−0.500** (−2.33)	
EPR		−0.204*** (−3.45)
Control	Controlled	Controlled
YEAR	Controlled	Controlled
AREA	Controlled	Controlled
Constant	4.058** (2.25)	9.646*** (4.38)
F	47.48	57.80
Adj R^2	0.357	0.322

***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

collection system and networking transmission system of the transportation industry need to be substantially formed and deeply integrated with the electronics, communications, Internet and other industries by 2025. The Ministry of Transport also issued the *Action Plan for the Development of Comprehensive Transportation Big Data (2020-2025),* which clearly defines the specific content of the digital development of the transportation industry, points out the need to guide the opening and innovation of big data, promote enterprise integration and innovation, and proposes the utilization of social capital for innovative applications of big data to promote the development of the industry's big data market. The digital transformation policy, which utilizes digital technology to break through key technologies and empower green development (Genzorova et al., 2019), undoubtedly promotes the digital transformation and development of transportation companies. However, what impact does policy have on the green innovation capabilities of these companies? Based on this, this study adopted the Difference-in-Differences (DID) method to further explore the impact of digitalization policies on the green innovation of transportation companies.

The transportation companies involved in digital transformation were categorized into two groups using PSM propensity score matching: the experimental group, which participated in digital transformation (denoted as TREAT = 1), and the control group, which was not involved in digital transformation (denoted as TREAT = 0). Additionally, a time dummy variable POST was set, with POST = 1 representing the period after the policy was implemented and POST = 0 representing the period before the policy was implemented. Furthermore, DID was defined as the product of POST and TREAT. Using these variables, a baseline difference-in-differences model was constructed.

$$GREEN_{i,t} = \rho_0 + \rho_1 POST_{i,t} + \rho_2 TREAT_{i,t} + \rho_3 DID_{i,t} + Crontrols + \varepsilon \quad (9)$$

The regression results, as shown in Table 7, indicate that regardless of the selected proxy variables for green innovation, the focus of this study, the coefficients of the DID regression are consistently positive and statistically significant. This suggests that the digital policy has a significant promoting effect on green innovation in transportation companies. It is evident that the digital policy plays a crucial role in driving the integration of

digitalization and green transformation in the transportation industry, thereby facilitating its high-quality development.

8.2 Study on economic consequences

With the implementation of the "carbon peaking and carbon neutrality" strategy, green innovation in companies serves as an emphasized approach to environmentally friendly innovation. It not only contributes to economic growth through conventional innovative technologies but also mitigates the dual pressures of environment and energy (Liu et al., 2022; Xie and Jamaani, 2022), thereby reducing carbon emissions intensity. It has been proved that green innovation is a key element of green development strategy, which improves environmental productivity, promote energy conservation and environmental optimization by investing in environmental technology and using green technology to reduce environmental pollution, energy and raw material consumption, in order to reduce carbon emissions significantly (Cai et al., 2021; Yuan et al., 2022; Chang et al., 2023). Therefore, this study further investigates economic consequences of digital transformation in promoting green innovation, specifically examining whether green innovation can reduce carbon emissions intensity and achieve the goal of sustainable development. This study used the ratio of provincial carbon dioxide emissions to gross domestic product as a measure of carbon emissions intensity (*CR*). The following model is established:

$$CR_{i,t} = \tau_0 + \tau_1 GREEN_{i,t} + Crontrols + \varepsilon \quad (10)$$

The results are presented in Table 8. Using two measures, *PTI* and *EPR*, to assess green innovation, both coefficients show significant negative effects on *CR*, indicating that green innovation contributes to reducing carbon emissions intensity. Therefore, it can be observed that promoting the development of green innovation technologies in companies is an effective approach for achieving green transformation, reducing carbon emissions, and realizing sustainable development.

9 Conclusion and recommendations

This study explores the mechanisms and pathways through which digital transformation alleviates financing constraints in environmental transportation companies and promotes green innovation. Empirical testing was conducted using data from listed transportation companies in the Shanghai and Shenzhen stock exchanges during the period of 2011–2021. The research findings are as follows: 1. Digital transformation can stimulate green innovation in transportation companies. 2. Financing constraints play a mediating role between digital transformation and green innovation in companies. 3. Further research revealed that digital policies contribute to promoting green innovation in companies. Additionally, economic consequences study demonstrated that green innovation helps to reduce carbon emissions intensity. The main contribution of this study are: firstly, it focuses on economic effects of digital transformation in transportation companies, enriches relevant studies on transportation companies. Secondly, based on the perspective of financing constraints, the relevant conclusion not only enriches the research on digital transformation of transportation companies, but also provide new perspectives on promoting the role of company in digital economic. Thirdly, this study further discusses the practical effects of green innovation in transportation company, which provide companies references for sustainable development.

Based on the above findings, this paper presented the following policy recommendations:

(1) Vigorously promoting the digital transformation of transport companies, boost digital economy transit to a new stage of deepening application and universal sharing, apply green governance as guide for future development. Strengthen the demonstration effect of digital transformation in large transportation companies, with target of green transformation, build a digital platform through comprehensive and systematic promotion of digital transformation, promote overall operation efficiency, achieve synergies, help transportation companies with sustainable development. The application of the Internet of Things and Big Data implement information exchange between vehicles, infrastructure and vehicles, in order to improve efficiency and safety of transportation system. It can also help transportation department to predict and optimize routes by using Big Data and to provide better customer service. In the meantime, ensuring data security, simplifying system processes, improving the accessibility and operational efficiency of the transportation system are also significant functions of using digital technology. Therefore, transportation company managers should combine the actual situation of the companies, choose an appropriate path of green transformation, accelerate construction of information network infrastructure, promote and upgrade smart infrastructure, introduce advanced information technology and management system, enhance transparency and efficacy of project management, reduce management costs, improve security and reliability of the system.

(2) Use digital technology to expand resources, alleviate companies' financing constraints, facilitate the promotion of green innovation. Application of digital technology helps transportation to access various data resources with high dimensions, wide coverage and large volume in capital market, promote transparency and accuracy of information delivery. Facilitate the digital transformation progress of transportation companies, combine the companies with differentiated development patterns at different stages and in different modes, to build diversified green cooperation model, follow policies to maximize fiscal policy effect, make rational utilization of government subsidies to solve the financial issues of transportation companies. Use digital technology for full access to capital market information, standardize the data processing in financing procedural, expand the boundary of company governance from offline to online, enhance the communication between companies and markets, strengthen security risk assessment, and monitoring and early warning, cooperate with high quality partners to reduce financing risk.

(3) Complete the institutional system of digital and green development, construct a reasonable green innovation development policy for transportation companies. Apply government policies to guide transport companies towards green innovation, which help companies to enhance initiative to innovate, thus to achieve win-win situation of sustainable

development and reduction of envinmental pollution. Meanwhile, use green development as policy guide, and build a new model of coordinated governance among companies, government and society, strengthen implementation and control of all aspects of companies' green development, improve information transparency, and build a sharing mechanism for digital development.

The limitations of this study includes the following two main points: one is the limitation of defining digital transformation. This study follows the methods of existing literature, build relevant index of digital transformation by searching, matching and counting word frequencies on feature words, however, along with the development of digital technology, there are also limitations in feature words, which lead to potentially incomplete definition of digital transformation. The other one is that general applicability of the findings remains to be improved. This study only discusses the relationship between digital transformation and green innovation in transportation companies, which do not cover all industries. Therefore, future study should continue to develop the research, use diversified methods and data to explore the questions such as motivation, process, and consequences of companies' green transformation in various industries comprehensively.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

XW: Writing–original draft.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Can green finance policies accurately promote corporate environmental investment?—a comprehensive evaluation from multiple aspects

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The 28th United Nations Climate Change Conference, held in the United Arab Emirates at the end of November 2023, stated that climate action cannot be delayed and the financing and investment situation for adapting to climate change needs a qualitative leap. Vigorously developing green finance is one of the important ways to achieve this goal. The core question of this paper is: Can green finance policies promote enterprises' environmental investment? This article uses the formal implementation of the "Green Credit Guidelines" in 2012 as a quasi-natural experiment, bases on the micro data of A-share listed companies from 2004 to 2020, and adopts the difference-indifferences propensity score matching method (PSM-DID) to explore the role of green credit policy in guiding corporate environmental protection investment from multiple dimensions. The research shows that the implementation of the "Green Credit Guidelines" has promoted corporate environmental protection investment to a certain extent, and the conclusion still holds after a series of robustness tests. Heterogeneity tests found that the impact of green credit policy on corporate environmental protection investment varies significantly among different ownership enterprises and enterprises in different regions. Further research shows that the Green Credit Guidelines are regulated by macro and meso factors. From the perspective of mechanism, this paper finds out the mechanism of promoting enterprises' environmental protection investment at the micro level. At the macro level, economic policy uncertainty and monetary policy tightening affect the degree of corporate environmental protection investment. At the meso level, the government's attention to environmental protection determines the behavior of local enterprises, which in turn affects the attitude of enterprises towards environmental protection investment activities. At the micro level, the implementation of green credit on the one hand exacerbates the problem of corporate financing constraints, making companies have incentives to invest in environmental protection to alleviate this problem. On the other hand, it will also promote changes in innovation and capital factors in enterprises, directly increasing corporate environmental

protection investment. This paper is helpful for the theoretical circle and management departments, so as to provide reference for the government to issue relevant policies.

KEYWORDS

green credit policy, corporate environmental investment, PSM-DID, financing constraints, factor substitution effect

1 Introduction

At present, the global extreme weather is frequent, the conflicts caused by energy crisis are increasing, and the environmental problems are increasingly prominent, as a result, the demand for sustainable development is pushed to a new peak again and again, and the green action is urgent.

Commercial and industrial activities are one of the main factors causing environmental degradation (Agliardi et al., 2017). As an influential presence in daily life, enterprises bear significant social responsibility. Environmental investment is the most direct manifestation of corporate environmental management activities. However, environmental investment itself has certain particularities. It has strong externalities and usually involves large investment scales and long return cycles. Therefore, it requires the dual effects of external factors such as relevant government policies and internal factors such as corporate social responsibility to promote enterprises to carry out environmental investment activities (Zhang et al., 2021).

Due to the strong leverage of banks, it is not uncommon to see that investment through banks to promote enterprises to adopt more environmentally friendly and sustainable development strategies (Sun et al., 2019). As early as 1974, the Federal Republic of Germany established the world's first policy-based environmental protection bank, which specialized in providing preferential loans for environmental projects that were not accepted by general banks (Stoeppler et al., 1984). Subsequently, the Superfund Act, the Equator Principles, and the Environmental Responsibility Economic Alliance were introduced and established, effectively promoting the sustainable development of economic sectors (Munitlak-Ivanović et al., 2017).

As the largest developing country and a responsible major country, China has been actively participating in global climate governance and environmental governance (Wu et al., 2016). In the 2022 Global Green Finance Development Index ranking, China is the only developing country among the top 10 countries in terms of green loan balance. By the end of the third quarter of 2023, China has become the world's largest green credit market and the second largest green bond market.

Without the strong support and promotion of the government, China's green finance would not have made such great progress and achievements. Green credit was first proposed in China in 2007, and since then, China's green credit has experienced rapid development and policy improvement. The "Green Credit Guidelines" issued in 2012 further elevated green credit to the level of corporate strategy. At present, scholars' researches on green credit policies(GCP) mostly focus on the impact on corporate green innovation (Hu et al., 2021), corporate performance (Yao et al., 2021), corporate structure upgrading (Wen et al., 2021), etc. There are few papers studying the relationship between GCP and enterprises' environmental protection investment, and most of the relevant

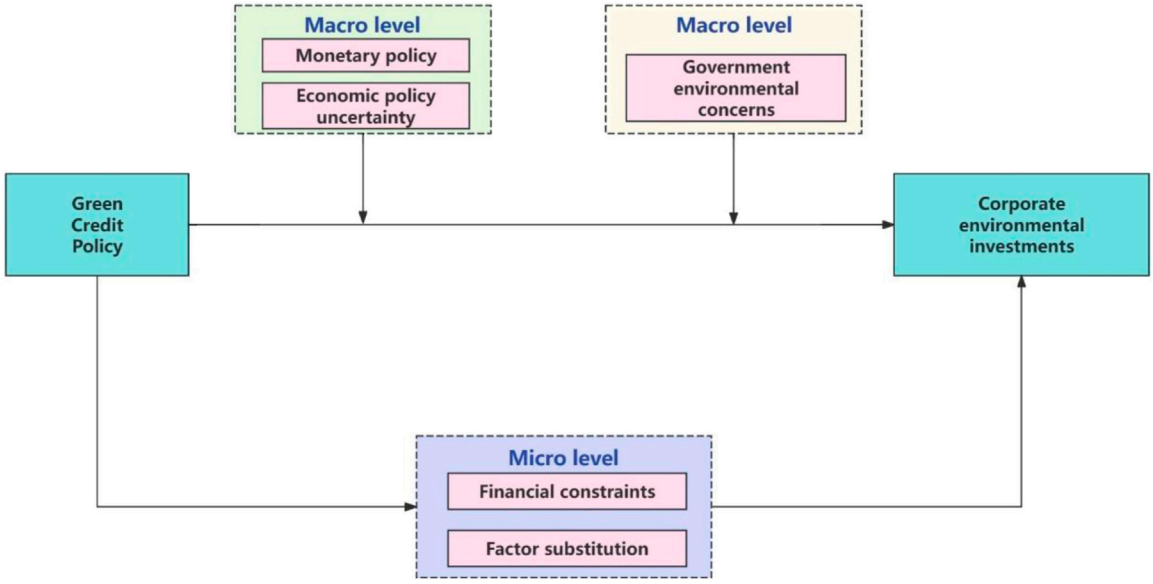


FIGURE 1
The mechanism of green credit policy affecting corporate environmental investment

papers take environmental protection investment as an intermediary variable to study the impact of GCP on other variables. For example, L. Ji et al. (2021) discussed the impact of GCP on the implementation of GCP. Whether the environmental protection investment of heavy polluting enterprises is conducive to promoting their debt financing. Few scholars have studied the direct causal relationship between GCP and environmental protection investment, and the discussion on the mechanism of action is not comprehensive, without taking into account the influencing factors at all levels. However, adequate investment in environmental protection is a necessary path for the green transformation of enterprises. Previous studies have theoretically demonstrated the path of mandatory environmental policies on enterprises' green innovation, environmental protection investment and green transformation, but there are no relevant studies to analyze whether market-based and guiding environmental policies can affect enterprises' environmental protection investment and what their impact path is. Therefore, the important question of the existing research is: Can the Green Credit Guidelines really play the guiding role of banks in capital allocation and promote enterprises' environmental investment?

Analyzing the role of guided environmental policies at the enterprise level can accurately evaluate the policy effect and better analyze the policy path. The purpose of this paper is: Can the Green Credit Directive promote enterprises' environmental investment, and what are the influencing factors? Based on this, this article constructs a quasi-natural experiment using the Green Credit Guidelines (hereinafter referred to as GCG) promulgated in 2012, takes China's A-share listed companies from 2004 to 2020 as the research object and use the PSM-DID method to evaluate the impact of green credit on corporate environmental protection investment and its mechanism of action, and study the mediating role of financing constraints and factor substitution effects. Compared to existing study, the possible research contributions of this article are: firstly, studying the relationship between green credit and corporate environmental protection investment provides empirical evidence for green financial policies to promote sustainable development of enterprises, helps to fully understand the policy effects of green credit, and also makes up for the relative scarcity of literature in this field. Second, it reveals the regulatory factors of green credit on enterprises' environmental protection investment from the macro and medium levels, analyzes the impact mechanism of green credit policy on enterprises' environmental protection investment from the micro perspective, and considers the influence factors of green credit policy at different levels more comprehensively, which helps to open the black box of green credit affecting enterprises' behavior. It expands the influence link of policy affecting enterprise behavior, and provides ideas and empirical evidence support for policy making of relevant departments and institutions at all levels. Thirdly, studying China's green finance can provide reference and ideas for financial policy reform and institutional development in other emerging developing countries. We built the theoretical framework shown in Figure 1 as a visual presentation of the article.

The remaining parts of this article are arranged as follows: the second part details the theoretical mechanism of the green credit policy's impact on corporate environmental investment and proposes research hypotheses; the third part is the research design; the fourth part is data description and benchmark regression results and analysis; the fifth part further studies the other factors of green credit policy affecting enterprises' environmental protection investment; and the last part is conclusions and implications.

2 Theoretical analysis and hypothesis

2.1 Policy background

Since the reform and opening up, China's economy has developed rapidly, and China has become the world's second largest economy. However, behind the economic development is an increasingly severe ecological environment problem. In the early stages of reform and opening up, due to the backward technology level and unsound industrial system, China adopted an extensive economic development model of "high investment, high consumption, high pollution, low efficiency", which seriously affected the ecological environment. In the late 1990s, Chinese enterprises began to participate in the global economic division of labor on a large scale, undertaking a large number of high-polluting and high-energy-consuming industries transferred from developed regions, leading to more serious environmental pollution and ecological degradation (Chan and Yao, 2008). In the new century, China rises as a "world factory", while behind this economic miracle is the blowout development of low value-added, high energy-consuming and high-polluting industries and the surge in population further deepens people's destruction of the ecological environment and their demand for the environment.

Faced with the continuously severe ecological environment situation, although the country has implemented certain environmental governance measures and thus improved the ecological environment in some areas, the overall situation is still deteriorating. The governance capacity is far behind the speed of destruction, resulting in a gradual expansion of ecological deficit. In addition, there are also many problems in China's environmental policies for local industries, which have led to the failure of the policy to achieve its expected results.

In recent years, the increasing natural problems caused by environmental degradation have made the society's demand for high-quality development stronger. All development is based on economic foundation, so is environmental governance. The funds needed for implementing environmental governance and green product projects can be obtained through green finance channels (Ng, 2018). Green finance mainly uses financial instruments as leverage to promote the development of environmental protection industry, green upgrade of traditional industries, and ecological environment protection projects to obtain financial support (Hemanand et al., 2022). The destructive development in the past decades has made many sicknesses of heavy pollution industries entrenched. Therefore, in addition to hard environmental policies, some guiding policies are also needed to promote the green development of industries. In order to implement the sustainable development strategy, the Chinese government has also issued a series of green finance policies.

The beginning of China's green finance policy can be traced back to the "Decision of the State Council on Strengthening

Environmental Protection Work during the Period of National Economic Adjustment", which was issued in 1981. From this point until 2012, it was the initial stage of the development of China's green finance policy. During this stage, China mainly adjusted the industrial structure and strengthened environmental protection through the issuance of "differentiated" credit policies (Zhang et al., 2021). In 1995, after the People's Bank of China established the "Notice on Issues Related to Implementing Credit Policies and Strengthening Environmental Protection Work", some domestic commercial banks began to issue green credits, and China's green finance system was officially born. The "Notice on Continuing to Deepen the Implementation of National Macro-control Measures to Effectively Strengthen Credit Management" issued in 2006 increased the difficulty for high-polluting and high-energy-consuming enterprises to obtain credit funds. The "Notice on Preventing and Controlling Loan Risks in High-energy-consuming and High-polluting Industries" issued in 2007 more strictly controlled the issuance of loans for high-polluting and high-energy-consuming projects. In 2012, the GCG issued by the CBRC promoted green credit from three aspects. First, the GCG requires banking financial institutions to promote green credit from a strategic height and increase support for green economy, low-carbon economy, and circular economy. Second, the GCG requires financial institutions to prevent environmental and social risks involved in credit business. Third, the GCG guides more credit resources to flow to green areas through adjusting the flow of bank credit funds and significantly reducing capital investment in high-energy-consuming enterprises (Wang et al., 2020). The promulgation of the GCG marks the rapid development stage of China's green finance policy.

2.2 Green credit policy and corporate environmental protection investment

Whether the green credit policy can effectively and accurately promote the green transformation of enterprises is the core issue in evaluating the effectiveness of the policy. Scholars have found that the green credit policy has significant financing punishment effects, which inhibit the new investment of heavily polluting enterprises, reduce the performance of enterprises in heavily polluting industries, and reduce the proportion of long-term debt of heavily polluting enterprises, affecting the scale and efficiency of investment (Wang et al., 2019; Yao et al., 2021). This shows that the implementation of GCG has led commercial banks to impose green credit constraints on heavy polluting enterprises. In the face of this negative externality, what measures will enterprises adopt? Existing studies on the effects of GCP mainly include two parts: some scholars believe that GCP can only promote industrial cleanliness. Due to the increased financing constraints of heavy polluting enterprises, the development of heavy polluting enterprises is inhibited (Yao et al., 2021). Another scholar found that GCP can force heavily polluting enterprises to carry out green transformation by reducing the level of long-term debt financing and increasing financing costs (Liu et al., 2019). Zhu et al. (2022) found the "guiding effect" of green credit policy on enterprise capital investment, that is, green credit can help improve the level of green transformation investment of heavily polluting enterprises. Therefore, after realizing the difficulties faced, heavy polluting enterprises will have the motivation to increase green investment and accelerate the process of green transformation, so that their own behavior and national policy trends are consistent, in order to avoid strict environmental regulation by the government.

The implementation of green credit policy is not completely harmful to heavily polluting enterprises. Some scholars have found that although the green credit policy restricts the financing costs of heavily polluting enterprises in terms of credit scale and interest rate, the increase in financing constraints is conducive to promoting enterprises to carry out technological upgrading in order to reduce compliance costs (Liu et al., 2019). Besides, corporate environmental protection investment can provide necessary financial support for corporate green innovation, thereby promoting enterprises to carry out green innovation activities (Zhang et al., 2020). In addition, the introduction of the green credit policy also implies the demand for green products in the corporate market, as a result, heavily polluting enterprises will promote the production of green products through environmental protection investment in order to occupy a larger market share.

Regarding the influencing factors of corporate environmental investment, scholars have pointed out that the external institutional environment will affect the environmental investment behavior of enterprises, and the greater the government intervention and the higher the legitimacy requirements of the social environment, the greater the environmental investment of enterprises (Huang and Sternquist, 2007). At the same time, the implementation of green credit policy makes the government and society pay attention to sustainable development and the depth of the concept of green development, stimulating the social responsibility of enterprises and then making investment behaviors in line with green standards.

Based on the above analysis, this article proposes:

Hypothesis 1. The implementation of green credit policy can promote enterprises' environmental protection investment.

2.3 Macroeconomic policies and corporate environmental protection investment

The common explanation for economic policy uncertainty is that it is difficult to form a definite policy expectation because the government has not clarified whether, when, and how to change the current policy (Le and Zak, 2006; Gulen and Ion, 2016). Economic policy uncertainty may lead companies to be unable to make clear decisions in such unpredictable circumstances, which in turn can have serious consequences for the company. Therefore, in today's era of global uncertainty, policymakers and corporate executives are highly concerned about it.

There are different views among scholars on the relationship between economic policy uncertainty and corporate investment. Vural-Yavas (2020) believed that during periods of high economic uncertainty, corporate managers would be more risk-averse and therefore avoid new investment projects. In addition, as uncertainty increases, the probability of corporate default also increases, resulting in increased debt financing costs. Therefore, when uncertainty is strong, banks may propose higher interest rates (Hong and Quang, 2023), which will have a negative impact on investment activities. However, some scholars believe that uncertainty can have a positive impact on corporate investment.

Kulatilaka and Perotti (1998) believed that uncertainty in the external environment can bring new potential development space for enterprises. The greater the potential development space is and the fiercer the market competition is, the more investment opportunities there are. This is consistent with the growth option theory (Bloom N, 2014) and the Oi-Hartman-Abel effect (Oi, 1962; Hartman, 1972; Abel, 1983), which believe that increased uncertainty can increase the size of potential project returns and thus increase corporate investment.

As part of corporate investment, environmental protection investment is also affected by economic policy uncertainty. In periods of high uncertainty, the macro environment is not optimistic. At this time, heavily polluting enterprises that are subject to credit constraints will face more difficult conditions for survival. In order to seek their own long-term development, heavily polluting enterprises have to make changes and take actions to comply with the overall sustainable development of society, which means the demand for long-term development will force these enterprises to invest in environmental protection.

Based on the above analysis, this article proposes:

Hypothesis 2. Economic policy uncertainty positively regulates the promotion effect of green credit policy on corporate environmental protection investment.

In China, the government is centralized and powerful, and the People's Bank of China, as the country's central bank, is directly under the State Council and occupies an important position in the national administrative system. Therefore, the monetary policy implemented by the central bank has a great influence. As an important economic policy of the country, monetary policy's impact on corporate investment behavior is also one of the core issues for scholars to explore the effectiveness of macroeconomic regulation. In response to this issue, scholars mainly conduct research from two aspects: laying economic foundation and alleviating financing constraints.

On the one hand, when the monetary policy environment is loose, companies tend to seize this opportunity and increase their financial asset reserves in a timely manner (Baumc et al., 2009), which lays an economic foundation for companies to invest in environmental protection. On the other hand, loose monetary policy can effectively reduce the cost of corporate loans by increasing the overall supply of funds in society, which can alleviate the problem of financing constraints to a certain extent (Morgan, 1998). The alleviation of financing constraints will promote companies to reduce cash holdings, expand investment (Kirch et al., 2019), and reduce the cost of environmental protection investment.

Based on the above analysis, this article proposes:

Hypothesis 3. Loose monetary policy positively regulates the promotion effect of green credit policy on enterprises' environmental protection investment.

2.4 Government's environmental concern and enterprises' environmental protection investment

As the middleman between national policies and enterprises, local governments play a "connecting link" role. In particular, in China's unique central-local structural relationship, the dynamic role of local governments is extremely important (Xu et al., 2009). On the one hand, local governments need to implement and carry out the macro policies issued by the state; on the other hand, the reflection and attention of local governments on policies will directly affect the behavior and attitude of enterprises.

The same is true for environmental issues. However, few scholars have conducted research on the relationship between government environmental concerns and corporate behavior. In China's current national conditions and institutional environment, the degree of government attention to the environment can directly affect corporate environmental governance investment decisions through the capital market (Rowe et al., 2010).

If local governments pay high attention to the environment, they will put pressure on heavily polluting enterprises, strictly control their pollutant emissions, and use incentives and constraints to make enterprises meet environmental compliance standards. This process is conducive to promoting the generation of environmental investment behaviors such as replacing fixed equipment and technological upgrading. If local governments pay less attention to the environment, they will not take too many environmental protection measures. In the absence of government pressure, punitive measures, and incentives, enterprises are more inclined to maintain their original production behavior, so there will not be many environmental investment behaviors.

Based on the above analysis, this article proposes:

Hypothesis 4. The government's environmental concerns will positively regulate the promotion effect of green credit on corporate environmental protection investment.

2.5 Micro-effects and corporate environmental protection investment

Allen (2005) found that in China, due to the dominant position of the banking system in the financial system, the financial model is dominated by credit, which makes bank credit determine the intensity of financing constraints (Brandt and Li, 2003).

Regarding the green credit policy and financing constraints, a large number of scholars have conducted research and reached a consensus. On the one hand, the implementation of the green credit policy has increased the difficulty for heavily polluting enterprises to obtain credit funds (Yao et al., 2021), which has exacerbated their financing constraints. On the other hand, credit regulations have a financing penalty effect (Peng et al., 2021), which restricts the investment and financing capabilities of heavily polluting enterprises (Fan et al., 2021), reduces the financing channels of enterprises (Hu et al., 2019), and these restrictions make heavily polluting enterprises unable to provide sufficient funds for investment, which inhibits their investment level. Environmental protection investment, as a unique investment, pursues comprehensive benefits including environmental, social, and economic benefits (Мельниченко et al., 2014). Therefore, under the condition of limited funds, financing constraints will reduce the environmental protection investment of enterprises.

Based on this, this article proposes:

Hypothesis 5. The green credit policy has an impact on corporate environmental investment through financing constraints, and the higher the degree of financing constraints, the weaker the positive effect of green credit on corporate environmental investment.

The factor substitution effect in the enterprise refers to the process in which the proportion of a certain production factor rises and gradually replaces other production factors. In this article, the factor substitution effect mainly refers to the implementation of GCG, which promotes the substitution of innovative factors for traditional inefficient capital factors.

GCG clearly require financial institutions to prioritize environmental compliance enterprises when allocating credit funds, which increases the difficulty of borrowing and financing for heavily polluting enterprises. If enterprises want to ensure long-term development under restrictive conditions, they must make a "clean" transformation (Wang et al., 2022), which will prompt enterprises with different pollution levels to make differentiated innovation investment choices.

Green credit policy is essentially a supplement to traditional environmental regulation policies. Therefore, most existing literature analyzes its green innovation effect based on the Porter hypothesis (1995). Scholars have found that the implementation of green credit significantly increases the innovation output of heavily polluting enterprises (Liu et al., 2021) and the output of green technological innovation (Gao et al., 2022). It can positively affect corporate green innovation by internalizing "environmental externalities" (G. Amacher et al., 2004).

The construction of green innovation projects is beneficial for heavily polluting enterprises to replace their existing inefficient and highly polluting facilities, equipment, and technologies. However, the development of green innovation cannot be separated from the role of investment. That is to say, changes in innovation factors drive changes in capital factors.

Based on this, this article proposes:

Hypothesis 6. The implementation of GCP can promote corporate environmental investment through factor substitution effects.

3 Study design

3.1 Samples and data

This article selects A-share listed companies from 2004 to 2020 as the research sample, with relevant data from the CSMAR database. The sample is classified into heavy pollution (experimental group) and non-heavy pollution (control group) industries.

In order to ensure the rationality of the sample, this article processed the original data according to the following three steps: ① removing all listed companies with "ST" and "*ST" in their stock abbreviations; ② removing companies in the financial and real estate industries; ③ removing severely missing data. After the above processing, the final sample included 531 listed companies, with 1,011 samples in the experimental group and 619 samples in the control group, with a total of 1,630 observations.

3.2 Variable selection and measurement methods

3.2.1 Explained variable

Corporate environmental investment (lnEEPI). In this article, the data on corporate environmental protection investment in 2017 and earlier years is replaced by sewage charges, while the data in 2018 and later years is replaced by environmental protection taxes. The two parts of the data are combined to form the data on corporate environmental protection investment.

3.2.2 Core explanatory variable

The difference-in-differences variable DID (treated*time). Among them, treated is a group dummy variable, with a value of 1 for the experimental group and a value of 0 for the control group. Time is a time dummy variable, with a value of 1 for years from 2012 onwards and a value of 0 otherwise.

3.2.3 Control variable

① Enterprise size (lnsize). Generally speaking, larger enterprises will pay more attention to green development for their own sustainability, thereby increasing their environmental protection investment. This article uses the logarithm of a company's total assets at the end of the year to measure the size of the enterprise. ② Enterprise age (lnage). Enterprise age represents the maturity of an enterprise. Generally, the higher the maturity of an enterprise, the more capable and energetic it is to make new investments, such as environmental protection investments. ③ Total operating revenue (lngrevenue). Total operating revenue is one of the important measures of a company's "blood-making ability". It is generally believed that the higher the total operating revenue, the stronger the willingness to invest. ④ Net profit (lnProfit). A high net profit indicates that the enterprise has good operating efficiency and greater investment possibilities. ⑤ Enterprise growth (Growth). Enterprise growth is a reflection of the comprehensive strength of an enterprise's total factors and also a guarantee for its sustainable development. This article uses the growth rate of operating income to measure it. ⑥ Variables related to corporate performance and governance structure. Considering the impact of factors such as corporate performance and governance structure on corporate environmental protection investment, we introduce return on assets (Roa) and capital intensity (Cap_inten). Among them, return on assets is represented by the ratio of a company's net profit to total assets; capital intensity is represented by the ratio of a company's total assets to operating income. ⑦Capital surplus (lncr). Capital surplus is the amount of capital invested in the enterprise by investors or others that exceeds the legal capital. Some environmental protection investors prefer to invest in companies with environmental responsibility and sustainable development strategies, so companies with large environmental protection investment efforts are more attractive to them.

3.2.4 Related variables for mechanism test

① Mediating variables: We select mediating variables from two aspects: the degree of financing constraints and the factor substitution effect. (1) In terms of financing constraints, drawing on the research of Wang et al. (2020), we introduce financing constraints as a mediating variable, and refer to Kaplan and

Zingales (1997) to measure the degree of financing constraints using the KZ index. The higher the KZ index, the higher the degree of financing constraints of the enterprise. (2) In terms of factor substitution effect, we measure it using the ratio of net long-term investment, net fixed assets, net intangible assets, and total assets.

② The proxy variable for environmental concern draws on the method of Li-fe et al. (2014) and builds an environmental concern indicator variable based on the frequency of words related to "environmental protection" in the work reports of each provincial government.

③ Adjustment variables: The variables of monetary policy tightness and economic policy uncertainty were selected as adjustment variables. (1) The proxy variable of monetary policy tightness was measured by the growth rate of M2, which was calculated as (M2 in the current year - M2 in the previous year)/M2 in the previous year. The faster the growth rate of M2, the more the money supply increased, and the looser the monetary policy became. Conversely, the looser the monetary policy became. (2) The proxy variable of economic policy uncertainty was measured by the Economic Policy Uncertainty Index compiled by Scott R. Baker, Nicholas Bloom, and Steven J. Davis from Stanford University and the University of Chicago. The variable construction information is shown in Table 1.

3.3 Model design

GCG is a national economic policy that was officially implemented in 2012. This article uses the difference-in-differences method to evaluate the implementation effect of the policy, and designs the model as follows:

$$\ln EEPI = \alpha_0 + \alpha_1 Time + \alpha_2 Treated + \alpha_3 DID + \alpha_4 X + \varepsilon \quad (1)$$

Among them, lnEEPI is the data of enterprise environmental protection investment, Time is a time dummy variable used to divide the experimental period and the non-experimental period. In this article, the formal implementation of CGC in 2012 is used as the segmentation point between the experimental period and the non-experimental period, the value of 0 is assigned to 2011 and earlier, and the value of 1 is assigned to 2012 and later. Treated is a group dummy variable used to divide the experimental group and the control group. Heavily polluting enterprises are the experimental group in this article, with a value of 1; the remaining non-heavily polluting enterprises are the control group, with a value of 0. DID is the cross-product of the time dummy variable and the group dummy variable. It represents the policy effect of GCG and is the core explanatory variable in this article. X represents a series of enterprise-level control variables, including company size, age, total operating income, net profit, growth, return on assets, capital intensity, and capital reserves. ε is the residual term.

The application of the difference-in-differences method is premised on the exogenous nature of policy shocks. However, as China's domestic emphasis on green finance continues to increase and the concept of global sustainable development deepens, the endogenous nature of the implementation of GCG will cause certain biases in the estimated results. Therefore, this article introduces the propensity score matching method (PSM) to weaken the bias caused by differences in initial conditions between the experimental group and the control group. The basic idea is to find an individual j in the control group that is as similar as possible to individual i in the experimental group in terms of observable variables. The specific approach is as follows: First, estimate the propensity score of the sample using Logit regression. Then perform one-to-one nearest neighbor matching between the experimental group and the control group based on the propensity score values. Finally, obtain a control group that matches the experimental group.

To further clarify the path of green credit on corporate environmental investment, this article sets up models (2) and (3) based on the basic regression model:

$$KZ = \beta_0 + \beta_1 Time + \beta_2 Treated + \beta_3 DID + \beta_4 X + \varepsilon \quad (2)$$

$$\ln EEPI = \gamma_0 + \gamma_1 Time + \gamma_2 Treated + \gamma_3 DID + \gamma_4 KZ + \gamma_5 X + \varepsilon \quad (3)$$

Among them, KZ represents the degree of financing constraints. The meaning of other variables is consistent with that in model (1). Model (2) examines the impact of green credit on financing constraints, and model (3) represents the impact of green credit on corporate environmental protection investment while controlling for financing constraints variables. γ_3 represents the direct effect of green credit on corporate environmental investment, the product of β_3 and γ_4 represents the mediating effect of financing constraints. The specific steps for testing the mediating effect are as follows: Firstly, test the significance of the regression coefficient α_3 in model (1), if α_3 is significant, it indicates that the overall effect of green credit on corporate environmental investment is significant and further test is needed, otherwise end the test. Secondly, test the regression coefficient β_3 in model (2) and determine the impact of green credit on financing constraints. Finally, use model (3) to test the direct effect of green credit on corporate environmental investment and the mediating effect through financing constraints. Provided that both β_3 and γ_4 are significant, if γ_3 is not significant, it indicates the presence of a full mediation effect; conversely, it indicates the presence of a partial mediation effect.

Similarly, when testing the mediating effect of factor substitution effects, it is only necessary to replace the KZ data in models (2) and (3) with FS data.

4 Empirical analysis

4.1 Descriptive statistics and correlation analysis

The descriptive statistics of the main variables are shown in Table 2. According to Table 2, the mean value of lnEEPI is 12.51, the median is 13.14, which is higher than the mean value, and the standard deviation is 3.182. The maximum and minimum values are 18.88 and −3.507, respectively. It can be seen that there are significant differences in the amount of environmental protection investment among various enterprises in China, but the overall level is relatively high. In addition, Table 2 also shows that there are certain differences between various variables of enterprises. Therefore, it is particularly necessary to perform propensity score matching on the experimental group and control group and add appropriate control variables.

Table 3 shows the correlation between each variable. The results indicate that there is a strong correlation between the variables (significant at the 1% level). Except for a few variables, the correlation coefficients for most variables are less than 0.5, so

TABLE 1 Indicator selection and variable description.

Variable name			Description of variables
Explained variable	lnEEPI	Enterprise environmental protection investment	Taking sewage charge data for 2017 and before, and environmental tax data for 2018 and after
Explanatory variable	treated	group dummy variable	1 for the experimental group and 0 for the control group
	time	time dummy variable	1 for years from 2012 onwards and 0 otherwise
	DID	differential variable	treated × time
Control variable	lnsize	Company size	Natural logarithm of the total assets of the enterprise at the end of the year
	lnage	Company age	Natural logarithm of the length of time a firm has been on the market
	lngrevenue	Total operating revenue	Natural logarithm of total operating revenue of the enterprise
	lnProfit	Net profit	Natural logarithm of net profit of the enterprise
	Growth	corporate growth	Operating revenue growth rate
	Roa	return on assets	Ratio of net profit to average total assets
	Cap_inten	capital intensity	Ratio of total assets to operating income of the enterprise
	lncr	capital reserve	Natural logarithm of enterprise capital reserves
Further inspection	MPU	Monetary policy tightening	(M2 of the current year - M2 of the previous year)/M2 of the previous year
	EPU	economic policy uncertainty	Economic Policy Uncertainty Index
	FC	financing constraints	KZ index
	FS	factor substitution effect	(Net long-term investment + net fixed assets + net intangible assets)/total assets
	Attention	Environmental Concern	Natural logarithm of the frequency of "environmental protection" related words in the government work reports of various provinces

TABLE 2 Descriptive statistics of main variables.

Variable	N	Mean	p50	SD	Min	Max
lnEEPI	1,637	12.51	13.14	3.182	−3.507	18.88
DID	1,637	0.549	1	0.498	0.000	1.000
lnage	1,637	2.835	2.833	0.437	1.386	3.466
lngrevenue	1,637	21.86	21.70	1.359	18.17	26.17
lnProfit	1,637	18.925	18.926	1.586	7.401	24.137
Roa	1,637	0.0270	0.0300	0.0890	−1.648	0.542
Cap_inten	1,637	2.021	1.703	1.253	0.145	13.21
Growth	1,635	0.314	0.0610	2.328	−2.726	47.08
lnsize	1,637	22.42	22.27	1.232	19.76	26.50
lncr	1,620	20.55	20.59	1.377	6.709	24.30

there will be no serious multicollinearity problems in the subsequent regression analysis.

4.2 PSM matching results and analysis

Table 4 presents the results of 1:1 nearest neighbor matching on the sample. From the results, it can be seen that after matching, except for the enterprise size, the standard deviations of the remaining variables are all less than 10%, indicating that the variable characteristics of the treatment group and control group samples are relatively close after propensity score matching, with small deviations and good matching effect. Compared with the results before matching, the standard deviations after matching have significantly decreased. Among them, the deviation of company age decreased by 98.10%, capital intensity decreased by 87.20%, total operating revenue decreased by 63.50%, return on assets decreased by 60.00%, growth decreased by 50.50%, company size decreased by 49.00%, capital reserves decreased by 38.80%, and net profit decreased by 11.10%. In addition, most of the t-test results do not reject the null hypothesis that there is no systematic difference between the treatment group and control group, and the t-statistic values of all variables have decreased after matching, passing the balance test and meeting the requirements of the double difference balance hypothesis.

4.3 Benchmark regression results

This article conducted a double difference test on the full sample and the PSM sample, and the benchmark regression results are shown in Table 5. In Table 5, columns (1) and (3) are the estimated results without adding other control variables, and columns (2) and (4) are the results with adding other control variables. The estimated value of the interaction coefficient in column (1) is 0.993, which is significant at the 5% level; the estimated value of the interaction coefficient in column (2) is 0.662, which is significant at the 10% level, indicating that the implementation of GCG has a positive

TABLE 3 Correlation analysis of variables.

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. lnEEPI	—													
2. DID	.33***	—												
3.lnage	.08*	.38***	—											
4.lngrevenue	−.41***	−.10*	−.17***	—										
5.lnProfit	.01	.03	.07	−.15***	—									
6.Roa	.76***	.36***	.11**	−.31***	.05	—								
7.Cap inten	−.03	.03	.07	.15***	−.00	−.02	—							
8.Growth	.88***	.35***	.05	.01	−.07	.72***	.06	—						
9.lnsize	.47***	.19***	−.06	.12**	.00	.39***	.09*	.60***	—					
10.lncr	.14***	.03	.01	−.06	.18***	−.12**	−.01	.13**	.06	—				
11. Attention	.26***	.03	.02	−.01	−.03	.31***	−.02	.27***	.18***	−.33***	—			
12. FAR	.33***	.86***	.14***	−.01	−.01	.38***	−.01	.38***	.25***	−.03	.09*	—		
13. EPU	.04	.10*	.04	.10*	.05	−.10*	.04	.10*	.10*	.58***	−.55***	.06	—	
14. MPU	−.05	−.05	.02	−.10*	−.09*	.06	−.07	−.11**	−.11**	−.54***	.47***	−.03	−.87***	—
15. FC	−.00	−.33***	−.48***	.17***	−.14**	−.01	.05	.06	−.07	−.09*	.20***	−.16***	−.25***	.17***

Note: ***, **, * indicate significance at the 1%, 5%, 10% level, respectively.

TABLE 4 Tendency score matching results.

Variable	Matching	Average value		Standard deviation (%)	Deviation reduction (%)	t value
		Treatment	Control			
lnage	Before	2.895	2.675	49.70	98.10	9.030***
	After	2.893	2.898	−0.900		−0.210
lngrevenue	Before	22.03	21.69	25.60	63.50	4.530***
	After	22.04	21.91	9.400		1.970*
lnProfit	Before	19.02	18.75	17.30	11.10	3.080***
	After	19.01	18.78	15.40		3.160**
Roa	Before	0.0468	0.0465	0.700	60.00	0.130
	After	0.0462	0.0463	−0.300		−0.0600
Cap_inten	Before	1.893	2.072	−14.70	87.20	−2.730**
	After	1.886	1.863	1.900		0.470
Growth	Before	0.344	0.248	4.900	50.50	0.770
	After	0.285	0.238	2.400		0.570
lnsize	Before	22.55	22.26	23.80	49.00	4.160***
	After	22.55	22.40	12.20		2.590*
lncr	Before	20.63	20.45	12.50	38.80	2.240**
	After	20.63	20.52	7.700		1.630

impact on corporate environmental protection investment, and hypothesis 1 is established. In addition, from the regression results of control variables, the increase in company age, growth, and capital reserves will all lead to an increase in corporate environmental protection investment, indicating that there is a positive correlation between corporate "strength" and corporate

TABLE 5 Impact of GCG on enterprise environmental protection investment.

Variable	Enterprise environmental protection investment			
	Full sample		PSM sample	
	(1)	(2)	(3)	(4)
DID	0.993**	0.662*	1.139**	0.673*
	(0.003)	(0.020)	(0.001)	(0.018)
treated	1.805***	1.529***	1.744***	1.525***
	(0.000)	(0.000)	(0.000)	(0.000)
time	−2.554***	−2.116***	−2.720***	−2.102***
	(0.000)	(0.000)	(0.000)	(0.000)
lnage		1.951***		1.995***
		(0.000)		(0.000)
lngrevenue		0.381		0.410
		(0.151)		(0.137)
lnProfit		−0.093		−0.0880
		(0.279)		(0.316)
Roa		−2.211		−2.039
		(0.243)		(0.323)
Cap inten		−0.044		−0.0320
		(0.737)		(0.820)
Growth		0.028		0.061***
		(0.285)		(0.000)
lnsize		0.252		0.202
		(0.388)		(0.505)
lncr		0.177**		0.188***
		(0.002)		(0.001)
_cons	13.031***	−8.246***	13.085***	−8.244***
	(0.000)	(0.000)	(0.000)	(0.000)
N	1,637	1,398	1,393	1,393
R2	0.217	0.455	0.234	0.457

Note: t values are in parentheses; ***, **, * indicate significance at the 1%, 5%, and 10% levels, respectively.

environmental protection investment. Columns (3) and (4) are the regression results of the PSM sample, which are the same as the regression results of columns (1) and (2) for the full sample.

4.4 Robustness test

To verify the validity of the difference-in-differences regression results and enhance the reliability of the results, this article conducted robustness tests by restructuring the experimental and control groups, removing other policy interventions, redefining proxy variables, and conducting a placebo test.

4.4.1 Reconstruct the experimental group and control group

We construct a new experimental group and control group by redefining the classification of heavily pollution industries. According to Di Zhou's classification method, we select 17 categories of heavy pollution industries, with specific industry codes of B06, B07, B08, B09, B10, C14, C15, C17, C18, C19, C22, C25, C26, C27, C28, C29, C30, C31, C32, and D44. This results in a new experimental group and control group containing 1,072 and 565 sample data sets, respectively. On this basis, we construct a new difference-in-differences variable for testing. The regression results are shown in Table 6, which are basically consistent with the benchmark regression results.

TABLE 6 The results of the double difference regression after redefining the heavily polluting industries.

Variable	Full sample		PSM sample	
	(1)	(2)	(3)	(4)
DID	0.932**	0.633*	1.066**	0.644*
	(0.005)	(0.027)	(0.002)	(0.024)
treated	1.805***	1.531***	1.744***	1.525***
	(0.000)	(0.000)	(0.000)	(0.000)
time	−2.543***	−2.103***	−2.715***	−2.098***
	(0.000)	(0.000)	(0.000)	(0.000)
lnage		2.000***		2.027***
		(0.000)		(0.000)
lngrevenue		0.437		0.196
		(0.096)		(0.520)
lnProfit		−0.0910		−0.0950
		(0.288)		(0.281)
Roa		−2.569		−2.476
		(0.181)		(0.237)
Cap inten		−0.0220		−0.165
		(0.866)		(0.306)
Growth		0.0300		0.0410
		(0.265)		(0.124)
lnsize		0.188		0.429
		(0.515)		(0.195)
lncr		0.179**		0.183**
		(0.002)		(0.001)
cons	13.031***	−8.302***	13.085***	−8.270***
	(0.000)	(0.000)	(0.000)	(0.000)
N	1,637	1,398	1,391	1,391
r2	0.208	0.452	0.223	0.452

Note: The values in parentheses are t-values; ***, **, * indicate significance at the 1%, 5%, and 10% levels, respectively.

4.4.2 Removing other policy interventions

Regarding the concurrent environmental policies that may interfere with the results of this article: the Environmental Protection Law of the People's Republic of China (hereinafter referred to as the "Environmental Protection Law"), which was officially implemented in 2015, adopts the following measures: adding a policy dummy variable for 2015 to the benchmark regression. If the result after adding the policy dummy variable for 2015 is not significant, it indicates that the impact of GCG on environmental protection investment is not significant, and the results of this article are not robust; if the result after adding the policy dummy variable for 2015 is still significant, it indicates that the results of this article are robust. The regression results are shown in Table 7. The coefficient of the interaction term changes slightly compared to the benchmark regression results, and it is still significant at the 10% level, so the results of this article are robust.

4.4.3 Replacing the proxy variable

The quantitative method of environmental protection investment in the main effect of this paper mainly takes into account the passive investment of enterprises in environmental protection due to government regulation. This article replaces enterprise environmental protection investment data. We refer to Zhang et al. (2022) for quantifying corporate environmental investment. Specifically, we define corporate environmental investment as the sum of capitalized and expensed corporate environmental expenditures. We use the variable of enterprise environmental protection investment obtained by this

TABLE 7 Regression results after removing other policy interventions.

Variable term	Full sample		PSM sample	
	(1)	(2)	(3)	(4)
DID	0.902**	0.620*	0.995**	0.604*
	(0.006)	(0.028)	(0.005)	(0.033)
treated	1.805***	1.519***	1.744***	1.515***
	(0.000)	(0.000)	(0.000)	(0.000)
time	−2.651***	−2.240***	−2.796***	−2.224***
	(0.000)	(0.000)	(0.000)	(0.000)
time3	2.138***	1.966***	2.199***	2.028***
	(0.000)	(0.000)	(0.000)	(0.000)
lnage		1.832***		1.914***
		(0.000)		(0.000)
lngrevenue		0.487		0.285
		(0.070)		(0.354)
lnProfit		−0.0680		−0.0770
		(0.424)		(0.369)
Roa		−2.506		−2.402
		(0.194)		(0.241)
Cap inten		−0.0120		−0.142
		(0.926)		(0.380)
Growth		0.0250		0.0370
		(0.394)		(0.251)
lnsize		0.164		0.362
		(0.579)		(0.277)
lncr		0.164**		0.172**
		(0.004)		(0.003)
cons	13.031***	−8.469***	13.085***	−8.496***
	(0.000)	(0.000)	(0.000)	(0.000)
N	1,637	1,398	1,391	1,391
r2	0.243	0.473	0.246	0.471

TABLE 8 Regression results after replacing the proxy variable.

Variable term	Full sample	PSM sample
DID	0.89*	0.87*
	(0.049)	(0.036)
treated	0.310	0.206
	(0.330)	(0.192)
time	−0.250	−0.142
	(0.548)	(0.346)
lnage	0.240	0.272
	(0.548)	(0.660)
lngrevenue	−1.84*	−1.62***
	(0.032)	(0.012)
lnProfit	0.220	0.312
	(0.354)	(0.426)
Roa	−5.330	−5.330
	(0.344)	(0.344)
Cap inten	−1.39*	−1.51*
	(0.033)	(0.047)
Growth	0.0200	0.0172
	(0.596)	(0.517)
lnsize	2.31*	2.18*
	(0.020)	(0.022)
lncr	0.120	0.341
	(0.470)	(0.651)
cons	−8.39**	−6.41**
	(0.004)	(0.015)
N	99	78
r2	0.490	0.307

quantitative method to carry out substitution variable test. This paper takes capitalized and expensed expenditures for environmental protection as proxy variables of corporate environmental protection investment to analyze the degree of influence of GCP on enterprises' active investment in environmental protection. Our empirical results are largely consistent with the benchmark regression results, indicating that the benchmark regression in this article is highly robust. The result is shown in Table 8.

4.4.4 Placebo test

Considering that the results of this article may be affected by other relevant time periods before the promulgation of GCG, a time placebo test was conducted by advancing the policy implementation time by 1 year to 2011 and re-constructing time dummy variables and interaction terms for regression. As shown in Table 9, regardless of whether other control variables were included, the obtained interaction term coefficients were not significant, indicating that advancing the policy implementation time would not significantly affect corporate environmental protection investment. Therefore, the policy effect is real and the results of this article are relatively reliable.

4.4.5 Heterogeneity test

The theoretical and empirical analysis results above indicate that the green credit policy significantly promotes corporate environmental protection investment. This article will conduct heterogeneity analysis from two aspects: corporate ownership and geographical location. In order to analyze the impact of corporate ownership, this article uses a triple difference model for testing. On

TABLE 9 Regression results of time placebo test.

Variable	(1)	(2)
DID2011	0.600	0.530
	(0.196)	(0.186)
treated	2.20***	1.66***
	(0.000)	(0.000)
time2011	−1.97***	−1.67***
	(0.000)	(0.000)
control variable	No	Yes
cons	12.58***	−7.67***
	(0.000)	(0.000)
Observation value	1,637	1,398
R2	0.190	0.440

the basis of formula (1), the corporate ownership variable is introduced to construct a triple difference variable DDD for estimation, as follows:

$$\ln EEPI = \alpha_0 + \alpha_1 Time + \alpha_2 Treated + \alpha_3 DDDgy + \alpha_4 X + \varepsilon \quad (4)$$

Among them, $DDDgy = DID \times GY, GY$ is the variable of corporate ownership, the value of state-owned enterprises is 1, and the value of non-state-owned enterprises is 0.

As shown in column (1) of Table 10, the impact of green credit on corporate environmental investment is more significant in state-owned enterprises. This may be due to the fact that state-owned enterprises, as the pillar of China's national economy, have a demonstration and leading role, and therefore are more proactive in responding to new national policies. On the other hand, state-owned heavy polluting enterprises are often the key monitoring targets for pollution control, and usually bear certain political functions and policy tasks, which make them more susceptible to environmental regulation policies (Tietenberg et al., 1989).

Columns (2), (3), and (4) in Table 10 are the regression results after dividing the sample into East, Central, and Western regions. From the regression results, it can be seen that the regression results of the cross-terms in the eastern region are significant at the 5% level and the coefficients are positive, indicating that the green credit policy has a strong promoting effect on corporate environmental protection investment in this region. However, the coefficients of the cross-terms in the central and western regions are not significant and are all negative, indicating that the green credit policy has no significant impact on corporate behavior in these regions. The reason may be that China's eastern region is economically developed, with relatively mature industries and mostly technology-intensive and financial services industries. The degree of pollution is not high, coupled with its own abundant funds, so it has the ability to carry out a series of environmental protection investments. While facing policy constraints, heavily polluting enterprises, as the main economic source in this region, have a more difficult time surviving under policy constraints. The lack of funds and the nature of the enterprise make it very difficult for them to carry out clean transformation, so it is reflected in the unclear policy effect.

5 Further analysis

The above analysis shows that the implementation of the green credit policy can promote corporate environmental investment to a certain extent, and the promotion effect is heterogeneous in different dimensions. As a macro policy tool, GCG have an impact on micro-enterprises. Therefore, this article explores the mechanism of GCG from the macro, meso, and micro levels.

5.1 Macro-level adjustment effect test

A large number of scholars have found a close relationship between macroeconomic policies and micro-enterprise financial behavior (Serven et al., 1992). As one of the important macroeconomic policies, monetary policy affects the country's money supply and market interest rates, which in turn affects the investment and financing behavior of enterprises.

To alleviate the high collinearity between the interaction term and the independent and moderator variables, this article performs a centralization process on the independent and moderator variables. The regression results of the test of the moderating effect of monetary policy tightening are shown in Table 11. The coefficient of the interaction term is significantly positive at the 5% level, indicating that the looser the monetary policy, the stronger the promotion effect of green credit on corporate environmental protection investment. Hypothesis 2 is established.

There is some controversy among scholars about the impact of economic policy uncertainty on corporate investment: some scholars believe that economic policy uncertainty brings opportunities to enterprises and helps them expand their investment scale (Wilson et al., 1975); while others believe that economic policy uncertainty will reduce corporate investment behavior (Almustafa et al., 2023; Liu et al., 2020). Although the conclusions are different, there is no doubt that economic policy uncertainty has a certain impact on corporate investment, so this article tests its moderating effect. The regression results are shown in Table 12. The coefficient of the interaction term is significantly positive at the 1% level, indicating that economic policy uncertainty plays a positive moderating role, and hypothesis 3 is established. The higher the economic policy uncertainty index, the less optimistic the macroeconomic environment, and the more difficult it is for heavily polluting enterprises subject to GCG to survive and develop. In order to preserve themselves, heavily polluting enterprises can only make themselves clean through continuous environmental protection investment to obtain more credit investment.

5.2 Meso-level adjustment effect test

The degree of environmental concern of regional governments largely determines the attitude of enterprises in this region towards green production and sustainable development, which in turn affects their environmental investment efforts. The results of the moderating effect test of environmental concern are shown in Table 13. The coefficient of the interaction term is significantly positive at the 1% level, indicating that the government's environmental concern plays a positive moderating role between green credit and corporate environmental investment. The higher the degree of concern, the

TABLE 10 Regression of heterogeneity test.

	(1)	(2)	(3)	(4)
	Ownership of enterprise	Eastern region	The central region	West China
DDDgy	0.43*			
	(0.034)			
DID		1.05**	−0.00	−0.390
		(0.006)	(0.998)	(0.506)
treated	1.99***	1.39***	1.63**	1.51***
	(0.000)	(0.000)	(0.004)	(0.000)
time	−1.77***	−2.68***	−1	−1.010
	(0.000)	(0.000)	(0.085)	(0.060)
lnage	1.85***	1.85***	2.24***	0.930
	(0.000)	(0.000)	(0.000)	(0.213)
lngrevenue	0.380	−0.260	1.60***	−0.440
	(0.153)	(0.501)	(0.000)	(0.455)
lnProfit	−0.0800	−0.150	−0.0600	−0.0200
	(0.342)	(0.198)	(0.698)	(0.926)
Roa	−2.200	−1.680	0.700	−6.810
	(0.247)	(0.452)	(0.896)	(0.277)
Cap inten	−0.0400	−0.380	0.43***	−0.54*
	(0.738)	(0.068)	(0.001)	(0.028)
Growth	0.0300	0.0300	−0.0300	−0.0500
	(0.313)	(0.297)	(0.786)	(0.894)
lnsize	0.210	0.98*	−0.96*	1.240
	(0.463)	(0.019)	(0.021)	(0.068)
lncr	0.18**	0.25***	−0.100	−0.120
	(0.002)	(0.001)	(0.382)	(0.476)
cons	−7.55***	−9.62***	−4.98*	−3.690
	(0.000)	(0.000)	(0.027)	(0.312)

stronger the promotion effect of green credit on corporate environmental investment. Hypothesis 4 is established.

5.3 Micro-level mechanism test

5.3.1 Financing constraints

The regression results of the mediating effect are shown in Table 14 and Table 15. The P-value of the Sobel test is less than 0.01, which is significant at the 1% level, indicating the existence of a mediating effect. Among them, supporting the hypothesis that financing constraints play a negative mediating role in the impact of green credit on corporate environmental protection investment, and hypothesis 5 is established. It can be seen that the introduction of GCP restricts the financing of heavily polluting enterprises and exacerbates their financing constraints. Therefore, under the pressure of limited financing, enterprises will have incentives to invest in environmental protection, thereby alleviating the difficulties of financing constraints.

5.3.2 Factor substitution effect

Tables 16, 17 reports the results of the mediation effect test of the factor substitution effect. It can be seen from the table that the P-value of the Sobel test is much smaller than 0.01, which is significant at the 1% level, indicating the existence of a mediating effect. This indicates that after the introduction of GCG, the development of heavily polluting enterprises has been greatly impacted. When financing difficulties increase and production costs increase to a certain extent, these heavily polluting enterprises will undergo factors substitution and technological progress in order to survive, which will ultimately promote the increase of corporate environmental protection investment.

TABLE 11 Test of the regulatory role of monetary policy.

	(1)	(2)	(3)
	model1	model2	After decentralization
DID	2.0215***	1.0391**	2.0625***
	(0.1264)	(0.5009)	(0.1279)
MPU	44.1262***	42.3223***	47.2581***
	(2.0538)	(2.2363)	(2.5683)
DIDMPU		8.9875**	
		(4.4341)	
DIDMPU_c			8.9875**
			(4.4341)
_cons	−16.8842***	−16.7918***	−17.3539***
	(1.2119)	(1.2114)	(1.2325)
control variable	Yes	Yes	Yes
N	1,398	1,398	1,398
adj. R2	0.5176	0.5187	0.5187

TABLE 12 Test of the moderating effect of economic policy uncertainty.

	(1)	(2)	(3)
	model1	model2	model3
DID	1.3274***	0.7717***	1.3222***
	(0.1155)	(0.2245)	(0.1152)
EPU	−0.0062***	−0.0069***	−0.0062***
	(0.0002)	(0.0003)	(0.0002)
DIDEPU		0.0013***	
		(0.0004)	
DIDEPU_c			0.0013***
			(0.0004)
_cons	−9.0126***	−8.7580***	−9.0603***
	(1.0875)	(1.0883)	(1.0848)
control variable	Yes	Yes	Yes
N	1,398	1,398	1,398
adj. R2	0.5569	0.5592	0.5592

TABLE 13 Test of the moderating effect of government's attention to the environment.

	(1)	(2)	(3)
	model1	model2	model3
DID	1.4566***	−0.7697	1.4325***
	(0.1419)	(0.5268)	(0.1410)
att	−0.2506***	−0.3670***	−0.2356***
	(0.0286)	(0.0389)	(0.0286)
DIDatt		0.2243***	
		(0.0511)	
DIDatt_c			0.2243***
			(0.0511)
_cons	−6.5337***	−5.3466***	−6.6364***
	(1.3422)	(1.3600)	(1.3330)
control variable	Yes	Yes	Yes
N	1,303	1,303	1,303
adj. R2	0.4063	0.4145	0.4145

6 Conclusion and Enlightenment

6.1 Conclusion

This article examines the impact of China's green credit policy on corporate investment behavior from the perspective of green finance. Specifically, this article constructs a quasi-natural experiment based on the Green Credit Guidelines issued in 2012, and uses the PSM-DID method to evaluate the impact of green credit on environmental protection investment of A-share listed companies from 2004 to 2020. The new conclusions found in this study are as follows: The study found that the implementation of green credit policy significantly promoted the environmental protection investment behavior of enterprises. Further analysis shows that from a macro perspective, economic policy uncertainty and monetary policy can positively regulate the promotion effect of green credit on enterprise environmental protection investment; from a meso perspective, government environmental concern plays a positive regulatory role between green credit and enterprise environmental protection investment; from a micro perspective, green credit policy can affect enterprise environmental protection investment through financing constraints and factor substitution effects. The heterogeneity test found that the green credit policy has different effects on enterprises with different characteristics. Specifically, compared with non-state-owned enterprises, the green credit policy has a more significant promoting effect on the environmental protection investment of state-owned enterprises; in terms of regional distribution, the impact of green credit policy on enterprise environmental protection investment is best in the eastern region, and the effect is not obvious in the central and western regions.

The research in this paper has obtained a wealth of conclusions, so it is necessary to compare with the previous work. This article has important theoretical value. It conducts in-depth analysis of corporate environmental protection investment in the field of green credit, which is rarely studied, increases the diversity of views in the field of green finance, enriches the theoretical basis for how to motivate enterprises to carry out environmental protection investment to achieve sustainable development goals, and responds to the call of Huang et al. (2021) that attention should be paid to

TABLE 14 Testing the intermediary effect of financing constraints.

	(1) lnEEPI	(2) lnfs	(3) lnEEPI
(Intercept)	12.325***	−1.106***	12.325***
	(0.071)	(0.013)	(0.068)
lnage	2.747***	0.200***	2.433***
	(0.201)	(0.038)	(0.194)
lngrevenue	0.515	−0.026	0.555
	(0.333)	(0.063)	(0.318)
lnProfit	−0.110	−0.039*	−0.048
	(0.104)	(0.020)	(0.100)
Roa	−1.245	−0.476	−0.499
	(2.538)	(0.479)	(2.426)
Cap_inten	−0.065	−0.034	−0.012
	(0.145)	(0.027)	(0.139)
Growth	0.034	−0.009	0.048
	(0.031)	(0.006)	(0.030)
lnsize	0.048	0.051	−0.031
	(0.367)	(0.069)	(0.351)
lncr	0.169*	0.020	0.139*
	(0.071)	(0.013)	(0.068)
DID	1.582***	0.239***	1.207***
	(0.148)	(0.028)	(0.146)
lnfs			1.569***
			(0.144)
R^2	0.395	0.126	0.449
Adj. R^2	0.391	0.119	0.444
Num. obs	1,243	1,243	1,243

Note. unstandardized regression coefficients are displayed, with standard errors in parentheses.
*p < .05. **p < .01. ***p < .001.

TABLE 15 Sobel test results of the effect of financing constraints.

Sobel-Goodman mediation test	Coef	Std Err	Z	P > Z
Sobel	−.11333253	.03037616	−3.731	.00019074
Goodman-1(Aroian)	−.11333253	.03062043	−3.701	.00021458
Goodman-2	−.11333253	.0301299	−3.761	.00016892

corporate environmental protection investment behavior. However, there are differences between this paper and the existing literature in terms of the mechanism of green credit policy affecting corporate behavior: Contrary to the conclusion of most scholars (Aastveit et al., 2017; Phan et al., 2021) that economic policy uncertainty will inhibit the economic behavior of enterprises, the empirical study of this paper finds that economic policy uncertainty can positively regulate the role of green credit in enterprises' environmental protection investment. That is, forcing companies to make green investments. This paper expands the research framework of economic policy uncertainty from the perspective of enterprise crisis sense and has new theoretical significance. In addition, this paper holds that the introduction of green credit policy exacerbates the financing constraints of heavily polluting enterprises, thus motivating them to make environmental protection investment to alleviate their difficult situation, which is different from the view of Chen et al.

TABLE 16 Factor substitution effect mediation effect test.

	(1) lnEEPI	(2) lnfs	(3) lnEEPI
(Intercept)	12.325***	−1.106***	12.325***
	(0.071)	(0.013)	(0.068)
lnage	2.747***	0.200***	2.433***
	(0.201)	(0.038)	(0.194)
lngrevenue	0.515	−0.026	0.555
	(0.333)	(0.063)	(0.318)
lnProfit	−0.110	−0.039*	−0.048
	(0.104)	(0.020)	(0.100)
Roa	−1.245	−0.476	−0.499
	(2.538)	(0.479)	(2.426)
Cap_inten	−0.065	−0.034	−0.012
	(0.145)	(0.027)	(0.139)
Growth	0.034	−0.009	0.048
	(0.031)	(0.006)	(0.030)
lnsize	0.048	0.051	−0.031
	(0.367)	(0.069)	(0.351)
lncr	0.169*	0.020	0.139*
	(0.071)	(0.013)	(0.068)
DID	1.582***	0.239***	1.207***
	(0.148)	(0.028)	(0.146)
lnfs			1.569***
			(0.144)
R^2	0.395	0.126	0.449
Adj. R^2	0.391	0.119	0.444
Num. obs	1,243	1,243	1,243

Note. unstandardized regression coefficients are displayed, with standard errors in parentheses.
*p < .05. **p < .01. ***p < .001.

TABLE 17 Sobel test results of factor substitution effect.

Sobel-Goodman mediation test	Coef	Std Err	Z	P > Z
Sobel	.32373089	.04922711	6.576	4.824e-11
Goodman-1(Aroian)	.32373089	.0493566	6.559	5.416e-11
Goodman-2	.32373089	.04909728	6.594	4.291e-11

(2021) that supporting the development of green finance can reduce financing constraints and promote green innovation of enterprises. The conclusion of this paper can support the green credit policy to optimize the market structure and accelerate the liquidation of backward production capacity.

6.2 Policy advice and research are insufficient

Based on the previous analysis, this article proposes the following policy recommendations:

(1) We will strengthen support for green credit and use financial constraints to force enterprises to invest in environmental protection. As the dual carbon targets are proposed and the time is approaching, the requirements for green ecological environment governance are becoming higher and higher. In order to better play the role of green financial policies, the government should strengthen supervision and punishment, forcing enterprises with higher pollution levels to carry out "clean" reforms.
(2) Increase monetary policy supply and policy stability, with special emphasis on the role of local governments in green finance. This paper finds that monetary policy and macroeconomic policy uncertainty have an important impact on the role of green credit policy. Therefore, it is necessary to strengthen the stability of the government's monetary policy and economic policy.
(3) Attach importance to the implementation of top-level GCP by local governments. This study shows that the higher the government's attention to environmental protection, the more significant the promotion effect on corporate green investment. Therefore, government attitude largely determines the behavior of individual enterprises. In addition, due to the differences in the implementation effect of GCP among enterprises in different regions, the policy implementation effect in the central and western regions is not obvious. To solve this problem, the fundamental approach is to strengthen the attention of various governments in the region to the environment, increase the emphasis on sustainable development and green finance, and seek regional development in the balance of economy and ecology.
(3) Give full play to the leading and demonstration role of state-owned enterprises, and strengthen the green supervision and punishment of non-state-owned enterprises. State-owned enterprises are in a dominant position in many key areas and important sectors, and the Chinese government has also given them more funds. State-owned enterprises, which are in a dominant position in both economy and policy, should play a model role and lead more non-state-owned enterprises to respond to national policy calls. However, non-state-owned enterprises currently respond less actively to policies than state-owned enterprises. This can be achieved by adding corporate environmental protection levels and environmental indicators to the assessment of enterprises or their managers, and implementing necessary punishment measures to promote their environmental protection investment and other green financial activities.

However, there are also some shortcomings in this article: for the explained variable, this article uses data on pollution charges and environmental protection taxes instead of corporate environmental investment data, which inevitably involves subjectivity and some bias. This also points out several important directions for future research. Firstly, with more comprehensive and accurate disclosure and statistics in the field of green finance in the future, more objective and accurate indicators for corporate environmental investment evaluation and other indicators for measuring the sustainable development of micro-enterprises can be constructed. Secondly, the economic consequences of corporate environmental investment are also worthy of further research, which is not elaborated in detail in this article due to space limitations.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://data.csmar.com/.

Author contributions

RZ: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing–original draft, Writing–review and editing. YW: Project administration, Supervision, Validation, Writing–review and editing. RL: Conceptualization, Project administration, Funding acquisition, Validation, Supervision, Writing–review and editing

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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A green revolution in the making: integrating environmental performance and green finance for China's sustainable development

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Green finance initiatives are encouraged in the world to attain green economic milestones. Therefore, it is the centered area of research for the plethora of researchers across the globe. Instead of this significant transition to green finance, the study analyzed the Chinese data to explore the relationship between Green Finance, Green Technology innovation, and Environmental Performance from 2003 to 2022 in the Chinese context. We preferred the CS-ARDL and panel Quantile regression models for exploring our hypothesis and to examine the relationship of these variables. Our results validated that both green finance and green technology innovation have positive effects in both the long-term and short-term on the environmental performance in numerous Chinese cities. The statistical results showed that Green Finance and Green technology innovation reduce the amount of CO_2 emission. Hence our results confirmed that both Green Finance and green technology innovations are significantly contributing to the environmental quality of China as the selected cities considered for the study investigation are considerably more driven towards green initiatives. This research also discussed the potential for implementing policy interventions in the future to leverage the adoption of green technology and make a significant impact on the world's environmental quality as China is the biggest emitter of CO_2 emissions. The study places and puts forward valuable insights to the regulatory bodies that would likely help them in achieving sustainable milestones and would contribute to their long-term strategic landscape for the attainment of environmental objectives and heights.

KEYWORDS

sustainability, environmental regulation, green technology adoption, cross-sectional ARDL, China

1 Introduction

There has been a significant rise in global environmental crises over the past few decades. There is a growing concern among experts worldwide regarding issues such as climate change, biodiversity loss, deforestation, air and water pollution, ocean acidification, and resource depletion. These problems have the potential to cause significant harm to

ecosystems, human health, and the planet as a whole. To mitigate the negative effects of these challenges on our environment, it has become imperative to maintain sustainable practices (Mirzaei and Shokouhyar, 2023). In this endeavor, it is important to note that China plays one of the most crucial roles to be had, due to its substantial role in global manufacturing and trade. As a result of China's crucial role in the global economy, it is often referred to as "the world's factory" (Yetgin and Yilmaz, 2022). As China's economy continues to grow, the country is also facing the high environmental footprint that comes along with it, presenting a difficult task for sustainable development. There have been instances where China's strict environmental standards have lagged behind the country's fast economic development. Lax enforcement of environmental regulations brought substantial emphasis on economic expansion and has historically led to significant pollution and resource depletion. An important point for policy and research considerations in this context will be the impact of environmental regulations on the environment, and these regulations will need to be carefully analyzed (Peng et al., 2021). The goal of this study is to provide insight into how environmental regulations play a powerful role in the adoption of green technology in China. In this study, we highlight the mechanisms that enable sustenance amid the global industrial landscape as well as draw attention to this issue. China's rapid economic growth and development has led to significant environmental challenges that are a cause for concern. The country's rapid industrialization and urban development have led to major environmental challenges, such as air and water pollution, depletion of natural resources, and increased greenhouse gas emissions. The government of China has undertaken a journey toward transition to a more sustainable growth paradigm as a result of recognizing these challenges. Environmental regulations play a vital role in this transformation, as they set stricter standards for industries, encouraging them to adopt new technologies that are cleaner and more resource efficient as a result of these regulations (Li et al., 2022). These regulations need to serve not only as instruments for protecting the environment but as catalysts also for bringing about technological innovation and reorganizing the economy as well. As sustainable development goals are concerned, green technology plays an essential role in achieving the desired outcomes by minimizing environmental impact and increasing resource efficiency (Jahanger and Usman, 2023). Several factors play a role in industries adopting green technology, including economic viability, technological feasibility, regulatory pressures, and market demand, all of which are intertwined in a complex interaction of factors (Nyangchak, 2022). As China works to maintain a balance between growth and environmental protection, understanding how environmental regulations can influence the adoption of green technologies has become an increasingly important component of formulating policies that will provide long-term benefits (Doğan et al., 2023). This study examines how environmental regulations may influence the adoption of green technology within China's industrial innovation landscape, specifically in terms of green technology adoption and environmental regulations' influence on green technology adoption in China. Analyzing the mechanisms shaping technology adoption decisions in a rapidly developing economy enables a better understanding of sustainability. Our goal is to contribute to a more nuanced understanding of how regulations influence technology adoption (Lashitew et al., 2019). This study aims to achieve specific objectives. This study is focused on analyzing the environmental regulations in China about the sustainability standards set by international organizations and trying to determine whether or not they align with these sustainability standards. The purpose of this study is to find out how environmental regulations influence other industries in terms of green technology adoption. Identifying the relationship between green technology adoption and key environmental performance indicators, i.e (measure air pollution, water pollution, and carbon emissions. Providing a glimpse at China's progress in transitioning to greener technologies, as well as enhancing conservation initiatives, the report demonstrates China's commitment to balancing rapid economic development and environmental protection) (Serrano-García et al., 2023). The purpose of the study is to provide policymakers, industries, and stakeholders with actionable insights into the ways in which regulatory frameworks can be optimized in order to increase the adoption of green technologies. It provides policymakers, industries, and stakeholders with actionable insights into how regulatory frameworks can be optimized.

Aiming for an in-depth examination of the situation, this research will use quantitative analysis. The quantitative analysis involves a review of industry-level data on environmental regulations, technological adoption trends, and environmental performance indicators at the industry level (Cui et al., 2022). This study seeks to offer both academic knowledge and practical policy considerations by conducting an in-depth analysis of the impact of environmental regulations on the adoption of green technology in China. The findings of the study are to be interpreted as a result of the process of enhancing our understanding of how regulatory frameworks influence sustainability development in an industry as a result of the information obtained from this study. There is a need for policymakers to strike a balance between economic growth and environmental preservation to ensure that growth does not compromise the environment. Furthermore, it has been demonstrated that the insights gained from this research can provide industries with valuable perspectives on how to navigate the challenges and opportunities associated with green technology adoption within regulatory frameworks to facilitate its adoption. China has seen tremendous industrial expansion and is a major player in the global economic landscape, but it has also experienced serious environmental challenges. Scene. Consequently, the process of elucidating the mechanisms that are responsible for the persistence of sustainability inside the nation is of utmost importance as a precondition for its achievement. Many factors have a significant influence, including government regulations, incentives, and technical breakthroughs. Policies that encourage the use of renewable energy, the reduction of emissions, and the management of waste have the potential to profoundly impact industrial operations (Zeeshan et al., 2021a). Investigating these links can assist in determining whether there are complications or opportunities for firms to implement environmentally friendly technologies. To provide insights that can contribute to a more harmonious existence between economic growth and environmental wellbeing, the purpose of this study is to investigate the relationship

between rules that control the environment and green technologies. This will assist in informing strategies that contribute to the combination of economic growth and environmental wellbeing. As a result of the convergence of green finance and green technology innovation, it is believed that environmental performance will eventually balance out green financing in developing countries. The concept of green technology innovation should be recognized as one that will increase energy efficiency and increase the use of renewable energy resources, both of which will be beneficial to the environment (López and Palacios, 2014; López-Menéndez et al., 2014). Moreover, the increased innovation in green technology indicates a positive outcome for eco-innovation as a whole, as well as a way to generate a greater amount of clean energy. Thus, green financing can contribute to the development of clean energy research and development and the production of renewable energy. Furthermore, Haller and Murphy (2012), documented that investing in green technology leads to the growth of international financial support for green technology, resulting in better environmental performance combined with more green technology innovation. Accordingly, green innovation is vital for the sustainable development of a green economy and the sustainability of the environment (Chen et al., 2023).

Green finance can lead to more sustainable green technologies by relating environmental performance to green finance (Zhang, 2022). By improving environmental performance, individuals may build habitats that require less air pollutants, which may lead to more green technology innovation from policymakers (Yang et al., 2021). Second, Carrión-Flores and Innes (2010) documented the process of increasing green technologies is usually a long-term process, it is natural that the results of improved environmental performance will continue to grow year after year. Furthermore, government support for green technology may spur more R&D into renewable energy and clean energy production, resulting in less pollution (Ahmed et al., 2022). As a result of these findings, green technology innovation is influenced by the environment and green finance.

This paper is stimulating due to its potential to make significant contributions in various areas. Our investigation examined the one-way cause-and-effect connection between advancements in eco-friendly technology and the overall environmental impact over an extended period. In contrast to previous studies that focused solely on the impact of sustainable finance on environmental performance, this research takes a different approach. Through an analysis of balanced panel data from 2002 to 2016 across 57 countries, the study explored the connections between environmental performance, green finance, and green technology innovation. While Westerlund and Edgerton (2007) explore the integration of potential CSD into the cointegration test. We proceeded with further analysis, in which we analyzed the long-term implications of environmental performance and green finance as they relate to green technologies innovation on both a panel-level and on a sub-sample-level basis in emerging economies and non-emerging economies respectively, as well as in many sub-samples established as indicators of environmental performance. Thirdly, it is important to note that the impact of green finance and environmental performance on the development of sustainable technologies may vary according to the level of environmental performance, green finance, and sustainable management innovation in a country, which is determined by the combination of these factors. Additionally, we constructed six sub-samples (High-GI, High-GF, Low-GF, High-EPI, and Low-EPI). The purpose of this research is to determine whether there are any differences in the relationship between three variables: green finance, environmental management innovation, and environmental performance, when it comes to the underlying causes of each variable. Furthermore, previous studies on green technology innovation have often focused on companies from a single country to analyze this phenomenon. Yu et al. (2022) highlighted the collection of data from 57 countries, providing a broader perspective on the outcomes and implications of economic development. Our study findings suggest that over time, there is a balanced connection between environmental performance, green finance, and green innovation. As a result, policymakers must consider all three factors together, as any alteration in one factor can potentially affect the other two.

1.1 Theory literature and hypotheses

The best support for this study we found the theories that are related to the Green Economy and Ecological Modernization. Technology innovation and systemic changes in economic practices promote economic growth while protecting the environment. In this way, environmental performance can also be brought into consideration in the context of green finance and is therefore aligned with this notion. By adopting green technologies and focusing on environmental factors, sustainable development can be achieved. This study is also supported by the Green Economy theory which prioritizes ecological stability and resource conversion Daly (1970) which is based on the notion that natural assets continue to meet the resources and environmental services that are essential to our health and wellbeing while promoting economic growth and development. Due to this notion, researchers emphasize the importance of green finance and its role in transforming economies into greener trends. Likewise, the TBL theory by Høgevold et al. (2019) and Sholeh et al. (2020) explains that apart from economic focus, businesses should also prefer to focus on social and environmental factors to ascertain sustainability. The theory of green finance also suggests that green initiatives would be very impactful to achieve environmental sustainability (Wang et al., 2022a). Our paper variables relationship is based on the notion of the above theories.

2 Literature review

China is widely recognized as "World's Factory" a global manufacturing powerhouse due to its significant role in the manufacturing industry. In this study, we explore how the adoption of green technologies intersects with the regulatory framework of environmental protection. Green technologies and environmentally friendly technologies are integrated into China's industrial landscape. Using the causal relationship between regulation and technology adoption, this study examines how environmental regulations influence China's transition to sustainable practices. Chinese environmental policy is analyzed comprehensively from various sources, with a comprehensive synthesis of existing research, challenges and opportunities in adopting green technologies presented, as well as long-term

implications. China is a major global manufacturing hub with many sustainability challenges. This research examines some of those factors through systematic literature reviews.

2.1 Green finance and green technology innovation

A green finance activity is a financial activity that seeks to improve the environment through the organized use of financial resources. Although green finance plays a critical role in mitigating the effects of climate change, it remains underinvested despite its importance. A green finance program includes a variety of environmental objectives, such as reducing emissions from industry, reducing CO_2 emissions, preserving biodiversity, and improving water sanitation. As part of this program, green finance can also be used to finance social initiatives (Akram et al., 2020). The importance of Green Finance and Green Technology Innovation in advancing sustainable development can be illustrated by the recent research conducted on the intersection of these two fields. With the increasing use of green finance as a tool for transitioning towards a low-carbon economy, it has gained momentum as a catalyst for promoting investments, loans, and financial instruments that promote environmentally friendly initiatives (Tamasiga et al., 2022). Simultaneously, various studies have consistently demonstrated the close connection between successful Green Finance and groundbreaking Green Technologies. These technologies play a vital role in mitigating the impacts of climate change (Lazaro et al., 2023). The findings of the study emphasize the significant relationship between both of these domains, which exist in a mutually beneficial relationship. The Green Finance sector channels funds toward the exploration, advancement, and application of eco-friendly technologies to foster environmental wellbeing (Wang and Wang, 2021). Green Finance has gained more credibility from investors due to the scalability and profitability of these technologies, making it more appealing to new investors. This dynamic synergy has the potential to generate long-term ecological benefits, foster economic growth, and address climate change on a global scale (Moreno et al., 2023). Early studies in this field examined the effects of green financing policies on GTI in enterprise sectors, along with the various factors that drive green technology innovation within these sectors (Jiakui et al., 2023). The Chinese government has implemented several environmental policies due to its status as one of the world's largest polluters and the world's largest developing country. The policy aims to assist businesses in decreasing their energy consumption and emission levels by implementing environmentally-friendly innovations (Hao and Chen, 2023). Multiple executive orders were unable to bring about the "innovation offsets" anticipated by Porter because of this coercion; in fact, rather than promoting enterprise innovation, they stifled it (Gray and Shadbegian, 2003; Zhong and Peng, 2022). Corporate green innovation has been shown to be insufficiently impacted by many market-based policies (Ghisetti and Pontoni, 2015). There are fundamental differences between ordinary innovation projects and green innovation projects, and the latter have higher risks and a lower success rate as compared to the former, so they require a longer R&D process and increased costs, and external financial backing is necessary (Tseng et al., 2013). China has implemented various sustainable financing initiatives, including green bonds and green credits, to support its environmental policies and foster sustainable economic growth. This became more comprehensive and influential due to China's implementation of the GFPP (Green Finance Pilot Policy) in 2017. As part of the government's efforts to promote green finance reform, a pilot zone for green finance reform and innovation has been chosen in eight cities across four provinces (Zhang et al., 2023). These cities were motivated to enhance and revolutionize their existing green finance tools by establishing a robust green technological innovation system. According to this theory, GFPP has the potential to impact a company's external financing and green innovation choices by allocating financial resources to environmentally friendly firms that meet certain environmental criteria (Aizawa and Yang, 2010; Huang et al., 2022). Does the Green Business Partnership Program (GFPP) effectively promote corporate green innovations and have a significant impact on the green economy? There is still much to discover about these subjects, as they remain largely unexplored. Global warming has always been associated with ecological disasters and resource depletion since the 1960s Zheng et al. (2022), land problems Yang et al., 2022 reserve lessening (Abbas and Dogan, 2022). Globalization, the depletion of resources, pollution of the environment, and food crises are all factors that are bringing an increasing number of challenges to the world (Zhang et al., 2022a).

H1: Green finance and Green Technology Innovation have a positive relationship.

The hypothesis above describes that investments in green finance positively influence the development and adoption of green technologies, suggesting a synergetic relationship between green technology and green finance. According to this hypothesis, financial mechanisms will play a vital role in enabling technological innovation, which is necessary for sustainable environmental practices to be achieved.

2.2 Green finance, and environmental performance

Green finance has been researched for a long time as a means of improving a company's environmental performance, and prior research indicates that there is a favorable correlation between these two variables. In essence, an organization's level of financial responsibility is directly tied to its environmental impact. However, Zhang et al., 2022b, documented the concept of green finance, which involves providing financial support to projects that promote environmental sustainability, such as clean energy and technology. Based on existing literature, it has been found that the environmental impact of companies can be improved through the implementation of green finance, leading to better performance (Guang-Wen and Siddik, 2022; Zeeshan et al., 2022a). Moreover, Shi et al., 2022 documented that green finance had a positive impact on the performance of enterprises in regards to green operations. Indriastuti and Chariri (2021) highlighted that green investments lead to better financial performance as well as a sustainable business

model. According to the findings of this study conducted by Alola et al., 2021 it was found and concluded that to attain environmental sustainability at a high-income level, there may be a need to compromise on investment risk. Extensive research has shown that green finance has a notable impact on improving environmental outcomes within a firm. Thus, it is anticipated that green finance will have a crucial role in enhancing the sustainability capabilities of banking institutions in the midst of this epidemic due to its positive environmental impact.

Additionally, Hsu et al., 2021 examine the correlation between green finance and environmental performance in China. It is interesting to see the insights that emerge from studying how Chinese firms respond to environmental concerns through Green Finance mechanisms. The study revealed a strong link between the adoption of green finance practices and the enhancement of environmental performance among companies. This finding was based on an extensive dataset that spanned from 2014 to 2018. Based on the results of this study, it is evident that companies involved in Green Finance activities, such as issuing green bonds or accessing green funds, have a significantly higher success rate in achieving their environmental goals compared to companies that do not participate in such activities (Zeeshan et al., 2021b; Baldi and Pandimiglio, 2022). In addition to exploring the relationship between green finance and environmental performance, the study also investigates the impact of institutional factors, such as government regulations and policy support. Given the substantial investment China has made in advancing green finance over the last 20 years, these findings have a noteworthy influence on the governance of its industrial sector, ensuring it remains environmentally sustainable and economically competitive. The growing awareness of global climate change and environmental issues has led governments to adopt a variety of policies aimed at promoting the adoption of green technologies, including green brands and environmentally friendly technology, across different industries. Likewise, Weinhofer and Hoffmann (2010) documented that, there is green finance, such as green bonds, to minimize the impact on the environment (Zeeshan et al., 2022b; Li et al., 2023). Green finance, however, is just a representation of the government's attitude toward protecting the environment, whereas environmental innovation refers to their attitude towards resolving environmental degradation, as well as innovation in generating renewable energy and improving the efficiency of the utilization of energy (Liang et al., 2021; Wang et al., 2022b). There have been only a few studies that have explored the potential connections between green finance and environmental performance. However, no empirical tests have been conducted to determine if green finance can influence environmental performance. Developing sustainable products and processes based on the current performance of green finance and the development of environmental quality can provide valuable insights for governments to understand the relationship between green finance and environmental performance. By promoting green technology innovation, the government has the potential to enhance economic development and environmental performance. It is crucial for global development to prioritize environmentally friendly, green, and sustainable practices. Therefore, this study aims to understand the impact of green finance and green technology innovation on environmental performance, both in the short and long term.

H2: There is a significant association between Green Finance and the Environmental Performance

In this hypothesis, we examine the impact of green finance on environmental performance from a quantitative perspective. Based on the results, it is suggested that a major factor associated with sustainable policies and outcomes is financial investments in environmental sustainability. The purpose of this hypothesis is to explore how financial initiatives may influence environmental quality by directly impacting the overall quality of the environment.

2.3 Green Technology Innovation and Environmental Performance

The footprints regarding the relationship of these variables exist in the body of knowledge. Singh et al. (2020), and data was collected from 669 manufacturing firms in the United Arab Emirates. Their findings indicate that a firm's green innovation processes a crucial role in determining its environmental performance. Another study on 244 Malaysian large manufacturing companies was conducted and found that there is a strong connection between green innovation and both human resource management and green intellectual capital to improve the environment (Kraus et al., 2020). Moreover, Rehman et al., 2021a highlighted the results of 244 large manufacturing companies and found that green innovation was related to environmental performance. However, Yan and Zhang (2021) highlighted an analysis of green practices and environmental management in energy-intensive units showed a positive impact on the environment through a stochastic Frontier model that was developed between 2011 and 2017. Furthermore, Zameer et al. (2021) and Xie et al. (2022) documented an efficient and effective way to monitor, develop, and implement green practices that can contribute to the improvement of the environment. Their research suggests that by closely monitoring, developing, and implementing green practices, significant improvements can be made to the overall environmental conditions. However, (Luo, 2020), found that the use of green technology innovation to improve environmental performance is significantly correlated with the use of green technology innovation. However, this study analyzes the positive impact of technology innovation on environmental performance in the energy sector, using data from 136 companies over 10 years (2009–2019). The connection between green innovation, government subsidies, and environmental performance has become more evident in recent years, although there are still some controversial findings. Several studies have explored the correlation between different types of government subsidies and environmental performance s (Zeeshan et al., 2021a; Xie et al., 2022). However, previous studies have not been able to distinguish between different categories of government subsidies, including those aimed at environmental protection. The potential impact of green technology innovation within both of them has not yet been fully demonstrated in the current situation (Sharif et al., 2022). Environmental protection subsidies aim to guarantee the preservation of the environment and the regulation of pollution. To assess the impact of China's environmental subsidy policy, it is crucial to directly analyze the influence of these subsidies on the performance of heavy-polluting industrial sectors, specifically those involved in the production of heavy pollutants. This analysis

will help determine the effectiveness of these subsidies in safeguarding the environment (Pei and Pei, 2022).

H3: Green Technology Innovation is Postulated to Improve Environmental Performance

The hypothesis above suggests that advancements in green technologies directly contribute to the improvement of environmental performance, which illustrates that innovative solutions are essential to dealing with the challenges associated with the environment. Using green technologies for research and development will lead to more efficient resource use and reduced environmental degradation. Table 1 denote the variable definition and measurement of the study the same table pattern used by many researcher like (Zeeshan, Rehman, Ullah, Hussain, and Afridi, 2022)

3 Empirical methodology

3.1 Data, variables, models, and estimation techniques

After thoroughly examining the available literature and analyzing the data presented in this paper, we were able to carry out a comprehensive study on the effects of green finance, green technology innovation, and environmental performance in 280 Chinese cities having 16 types of heavy-polluting industries by using the data source which is available on: Ministry of Ecology and Environment, China City Statistical Yearbook and from CNRDS (http://www.cnrds.com) database which has been reported in this paper for the period 2003–2022. We selected those firms for which the green finance and GTI data are available in the Chinese database. The most relevant econometric techniques of this study are as follows Eq. 1:

$$EP_{it} = \alpha_0 + \beta_1 GF_{it} + \beta_2 GTI_{it} + e_{it} \tag{1}$$

Where EP depicts environmental performance Shao et al. (2023), α is the coefficient, GF denotes green finance Lee and Lee (2022) GTI represents green technology innovation Yang et al. (2023) and e is the error term. It was important to conduct this analysis to assess the normality of the data and evaluate the strengths and weaknesses of each variable. In addition, the CSD test was utilized to analyze cross-sectional dependency, which was considered suitable given the cross-sectional nature of the data. The cross-sectional dependency test is given in bellow equation Eq. 2:

$$CSD_{IT} = \left[\frac{IT(T-1)}{2}\right]^{\frac{1}{2}} \widehat{\bar{\rho}}_T \tag{2}$$

$\widehat{\bar{\rho}}_T$ denotes T stands for time, and I stand for cross-section units, this is what we see as a pair-wise correlation coefficient.

Furthermore, a cross-sectionally augmented IPS test (CIPS) is performed to assess the stationarity of the variables. Stationarity is a vital aspect to consider before applying a suitable model to a study. As a result, CIPS was also used. Eq. 3 CIPS are as follows:

$$\Delta W_{i,t} = \phi_i + \phi_i Z_{i,t-1} + \phi_{i\bar{Z}_{t-1}} + \sum_{l=0}^{P} \phi_{il} \Delta \bar{W}_{t-1} + \sum_{l=0}^{P} \phi_{il} \Delta W_{i,t-1} + \mu_{it} \tag{3}$$

$\bar{W}$ depict the mean "cross-sectional" and it is given in Eq. 4 equations:

$$W^{i,t} = \phi^2 EP^{i,t} + \phi^2 GF^{i,t} + \phi^3 LnGTI^{i,t} \tag{4}$$

Therefore, the CIPS establishes equation (5), wherever, CADF depicts the cross-sectional ADF test.

In previous studies, the Westerlund and Edgerton (2008) cointegration test was used to assess cointegration and determine whether it applies to the relevant model. This step is crucial for employing the appropriate model. In addition, when taking into account the distinctive characteristics of the durable CSD approach and making assumptions about structural breaks, it emerges as a highly efficient method for examining cointegration. Additionally, we explore how the structure varies during periods of regime shifts and non-regime shifts. Below is the equation for the test Eq. 6:

$$1Log(\mathrm{L}) = \alpha_0 - \frac{1}{2}\sum_{i=1}^{N}\left(\mathrm{Tlog}\left(\sigma_{\mathrm{i,t}}^2\right) - \frac{1}{\sigma_{\mathrm{i,t}}^2}\sum_{\mathrm{t=1}}^{\mathrm{T}} \mathrm{eit}^2\right) \tag{6}$$

It is also important to note that the previous literature applied the CS-ARDL technique to check the correlations between the constructs under study. There are several assumptions associated with this model, such as endogeneity, CSD, and slope heterogeneity. Furthermore, it can be noted that ARDL is an approach broadly used for panel data analysis, but it does not address the problem of CSD errors. It is therefore appropriate to deal with CSD issues in the best possible way using CS-ARDL. This is a novel approach developed by Chudik and Pesaran (2015) that also has some strict assumptions, which are related to these methods. An example of how the approach equation can be represented is shown below Eq. 7:

$$\Delta Y_{it} = \varphi_i + \sum_{\mathrm{l=1}}^{\mathrm{P}} \varphi_{it} \Delta Y_{i,t-1} + \sum_{\mathrm{l=0}}^{\mathrm{P}} \varphi_{\mathrm{il}}^{'} EXV_{s,i,t} + \sum_{\mathrm{l=0}}^{1} \varphi_{\mathrm{il}}^{'} \overline{\mathrm{CSA}}_{\mathrm{i,t-1}} + \varepsilon_{it} \tag{7}$$

Thus previous research also proposed the cross-sectional ARDL employing the understudy concept and stated as follows equation no Eq. 8:

$$\begin{aligned}\Delta EP_{it} = {} & \varphi_i + \sum_{\mathrm{l=1}}^{\mathrm{P}} \varphi_{it}^{'} \Delta EP_{i,t-1} + \sum_{\mathrm{l=0}}^{\mathrm{P}} \varphi_{it}^{'} \mathrm{GF}_{s,i,t} \\ & + \sum_{\mathrm{l=1}}^{\mathrm{P}} \varphi_{it}^{'} \mathrm{lnGTI}_{s,i,t} + \sum_{\mathrm{l=0}}^{1} \varphi_{it}^{'} \mathrm{CSA}_{i,t-1} + \varepsilon_{it}\end{aligned} \tag{8}$$

3.2 Panel quantile regression (PQR)

The study additionally used panel quantile regression, a method introduced by Koenker (2004) to understand the different heterogeneity of the dataset. Quantile regression has become a crucial instrument in environmental research in recent years. There are four strong reasons why quantile panels should be modeled based on a regression approach. By employing traditional regression analysis, researchers calculate regression coefficients based on average effects of covariates, rather than estimating coefficients using average effects. For more accurate regression coefficients, it is advisable to utilize this method as it accounts for the significant variations between predicted and observed variables. It has been noticed that the conditional mean does not consistently produce the same outcomes. PQR, on the other hand, does not rely on any assumptions about the distribution, including the absence of a normal distribution (Ouyang et al., 2022). In terms of the distinct heterogeneity of the panel data, there is no distinction between CM and PQR methods, which also incorporate the distributional

TABLE 1 Variables definition and measurement.

Variables	Symbol	Explanation and measurement	References
Environmental performance	EP	A strategy for protecting the environment is judged according to its average score. Measures of environmental performance include emissions, resource usage, waste management, and compliance with environmental regulations	Appannan et al. (2023), Du et al. (2023), Long et al. (2023)
Green technology innovation	LnGTI	This is a log (1+ the number of green patents awarded) of the number of green patents granted	Li and Li (2022), Huang et al. (2023)
Green Finance Index	GF	An index based on green credit, green investment, green management, and green insurance has been used. (Specifically, (1) Industry interest expenses are used to measure green credit. (2) Environmental pollution control investment is measured by GDP. (3) Agricultural insurance is measured by its share of agricultural output. (4) Budget expenditures for environmental protection are used to measure green management	Lee and Lee (2022) and Chen et al. (2023)

TABLE 2 Descriptive statistics.

Variable	Mean	Std	Minimum	Maximum
EP	5.131	3.420	0.798	10.697
GF	70.435	38.592	15.154	164.581
GTI	12.151	8.166	4.405	28.912

heterogeneity of the panel data (Akram et al., 2020). When studying PQR, it is important to measure the independent variables alongside the dependent variables to gain a thorough understanding of them. This approach sets itself apart from CM methods by not relying on distributional assumptions. In addition, it avoids making any normality assumptions, unlike the CM method. In comparison to CM, PQR also addresses outliers and produces reliable results. Due to the utilization of various quantiles in PQR, there exists a distinct relationship between the predicted and observed variables. Each cross-section is also explored for unobserved heterogeneity by measuring various parameters within the quantiles (Amin et al., 2020). Considering the coefficient at the extreme is also useful for policy purposes. Besides its econometric advantage, the PQR provides a multidimensional analysis of how GF and GTI are estimated at different stages of EP, offering a comprehensive analysis of these variables.

According to Eq. 9, Akram et al. (2021) the Panel Quantile Regression model can be summarized as follows:

$$Q_{Y_{it}}(\tau|X_{it}) = \gamma(\tau)'X_{it} + \alpha_i \quad i = 1, \ldots\ldots, N, t = 1 \ldots\ldots, T \quad (9)$$

Here Y_{it} is the DV EP, $Q_{Y_{it}}(\boldsymbol{\tau}/\boldsymbol{X_{it}})$ denotes to the τth quantile of EP, $\boldsymbol{X_{it}}$ signifies the vector of IV (GF, GTI) in year t for i country. While, $\gamma(\tau)$ denote to unidentified coefficients, α_i shows the effects of a specific country are unknown. While i shows the Chinese cities and t represents the year. This study presents a successive model Eq. 10 Iuliano et al. (2018) that will be used to analyze the data.

$$Q_{Y_{it}}(\tau|X_{it}) = \gamma_{1\tau}GF_{it} + \gamma_{2\tau}GTI_{it} + \alpha_i \quad (10)$$

In the case of Panel Quantile Regression, a traditional linear regression model cannot be used to estimate the model. Likewise, Koenker (2004) documented that with the elimination of an unknown part of the estimation process, it is possible to minimize the estimation process by offering a penalty term. Compared to other approaches, this method has two distinct advantages over the others. Additionally, it minimizes variance caused by distinct coefficient estimation by decreasing the estimated parameters efficiently (Akram et al., 2020). It has been estimated that the Eq. 11 in this way:

$$\underset{\beta}{argmin} \sum_{m=1}^{M}\sum_{i=1}^{N}\sum_{t=1}^{T} WM\rho_{\tau m}\left[Y_{it} - \gamma_{1\tau}\mathrm{GF}_{it} - \gamma_{2\tau}\mathrm{GTI}_{it} - \alpha_i + \mu\sum_{i=1}^{N}|\alpha_i|\right] \quad (11)$$

$\rho_t(\gamma) = \gamma(\tau - 1_{(\gamma<0)})$ check function, 1_A It indicates that set A has a function of an indicator. Whereas, Y_{it} specifies the EP in the country i in time t. In this case, M stands for the quantile index, first, we check whether data have the attributes of normality, stationarity, and heterogeneity along with the econometric method mentioned above. Using a panel quantile regression model, this study confirms non-normality, stationarity, and slope heterogeneity. Data are first normalized, stationary, and heterogeneous in slope before applying the above method. Using a panel quantile regression model, this study confirms non-normality, stationarity, and slope heterogeneity.

4 Results and findings

The findings regarding the descriptive statistics indicate that the Environmental Performance variable has a mean value of 5.131. This variable serves as a measure of the effectiveness of environmental protection strategies in safeguarding the environment. On the other hand, the average value of the Green Finance variable was found to be 70.435. This variable is a composite index that takes into account factors such as Lev, Share, Share and Size. Lastly, the mean value of Green Technology Innovation was determined to be 12.151. This variable is quantified using the logarithm of one plus the number of green patents granted. These results are summarized in Table 2.

This research employed descriptive statistics to examine the distribution of variables across different years. Specifically, the analysis focused on determining the levels of the variables for each year and calculating their respective mean values. Descriptive statistics were employed to estimate the level of each variable by year, thereby providing an analysis of the data for the temporal dimension. The data unveiled indicates that the year 2020 exhibited the most noteworthy degree of environmental performance and green finance. In contrast to previous years, the year 2016 witnessed a notable surge in the rate of innovation within the realm of green technology. The breakdown of these values is presented in Table 3.

TABLE 3 Yearly base descriptive statistics.

Year	EP	GF	GTI
2001	4.182	55.004	11.053
2002	4.248	53.053	11.168
2003	4.452	55.619	11.283
2004	4.653	57.841	11.399
2005	4.745	59.752	11.515
2006	4.884	64.469	11.630
2007	5.037	67.016	11.432
2008	5.172	65.674	11.219
2009	4.991	69.548	12.920
2010	5.282	71.511	12.247
2011	5.432	70.813	11.535
2012	5.511	74.294	11.912
2013	5.544	76.745	12.517
2014	5.561	79.587	12.605
2015	5.380	81.854	13.731
2016	5.291	80.147	13.735
2017	5.371	79.647	12.699
2018	5.469	78.886	12.950
2019	5.538	80.960	13.121
2020	5.879	86.273	12.328
2021	5.498	81.051	13.024
2022	5.508	81.161	12.976

It is suggested by the provided tables that the research could assess the relationships and trends between these variables, in addition to the potential underlying factors that may influence their behavior. There is a lot of information that may be useful in making informed decisions, formulating policies, or gaining a much broader understanding of broader economic or social dynamics, depending on the variability, trends, and potential interactions between these variables. A deeper analysis of the relationships between these variables could be revealed through further analysis, such as a regression or correlation analysis. In addition, the results of this study may explain trends and variations observed over time.

Figure 1 show the descriptive and statistical graph of the data (Slough, McTigue, Kim, and Jennings, 2010). The correlation of the variables has been examined in Table 4 to confirm whether there are strong or weak relationships between them. Based on the results of Table 5, it appears that the correlation between Green Finance and Green Technology Innovation and CO_2 emission is negative which means that both GF and GTI reduce CO_2 emission and enhance the level of environmental quality.

Also in Table 5, the cross-sectional dependence test values show statistically significant values which confirm that there is cross-sectional dependence in the data.

Table 6 Cross-sectionally the stationarity of variables, we conducted a cross-sectionally augmented IPS (CIPS) unit root test to analyze the stationarity of variables in Table 6. During the estimation process, we found that the "EP and GTI are stationary at the first difference, whereas the GF are stationary at the level.

Based on the footprints regarding stationarity, we proceeded with applying cointegration techniques to find out if there exist any long-run relationships between the variables. The data in Table 7 Cointegration test showed that all probability values are statistically significant which declared the cointegration among variables.

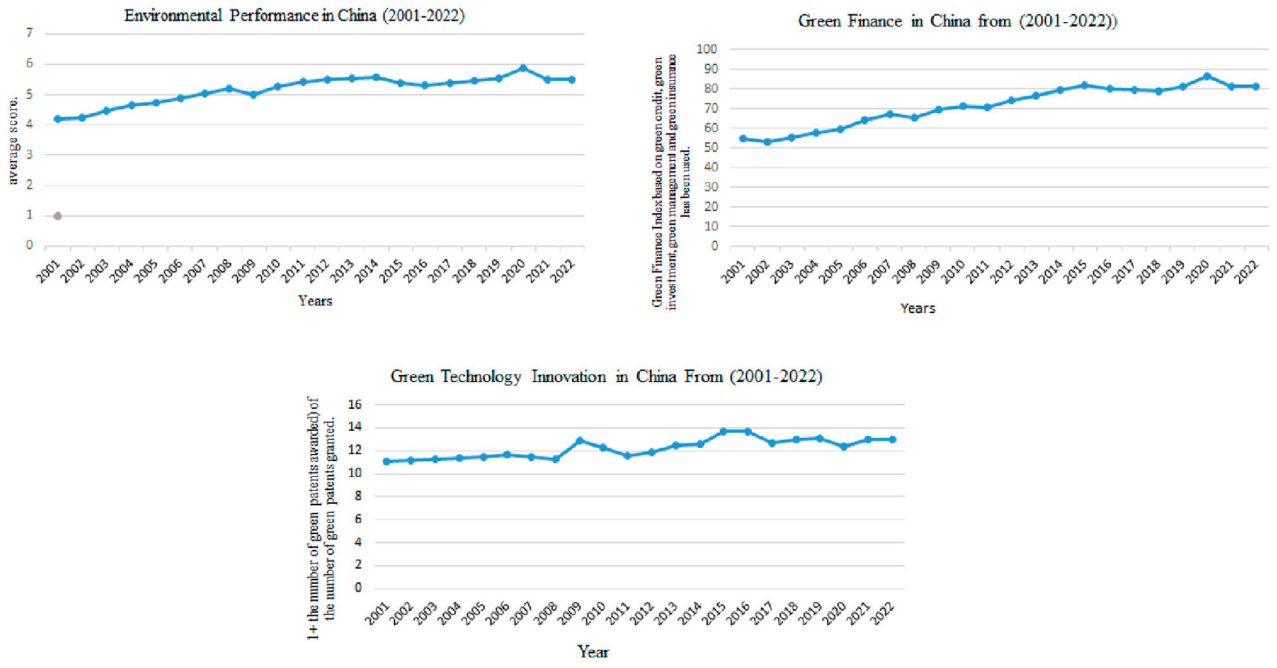


FIGURE 1
Descriptive statistics graphical form and stylized fact.

TABLE 4 Correlation analysis.

Variables	EP	G.F	GTI
EP	1.000		
GF	−0.197	1.000	
GTI	−0.039	0.466	1.000

TABLE 5 Cross-sectional dependency test.

Variables	T-statistics
EP	4.902***
p-value	(0.000)
GF	3.299***
p-value	(0.000)
GTI	5.663***
p-value	(0.000)

TABLE 6 Cross-sectionally augmented IPS (CIPS) unit root test.

	Level I (0)		1st diff I (1)	
Variables	CIPS	M-CIPS	CIPS	M-CIPS
EP	−2.495***	−4.413***	0.001	0.000
G.F	0.000	0.001	3.312***	5.253***
GTI	−4.673***	−5.294***	0.000	0.001

4.1 CS-ARDL

To know the impact of Green Finance and Green Technology Innovation on Environmental Performance we conducted a CS-ARDL estimator as a main frame econometric technique and the results in this regard are displayed in Table 8 which provides an overview of these values. This technique shows both short-term and long-term relationships between EP, GF, and GTI, the research done using CS-ARDL analysis suggests that there is a statistically strong association between (GF& CO_2 and GTI and CO_2) these variables in the long run and the short term. GF and GTI are associated with increases in EP, as both show an inverse relationship with CO_2 a proxy for Environmental Performance. In addition, a significant error correction term appears that indicates that any deviation from the long-run equilibrium tends to be corrected by the system when it performs a short-run analysis.

4.2 Panel quantile regression (PQR)

Table 9 PQR results explain how GF and GTI, affect the EP. For a comprehensive analysis of the impact of GF on EP, the study used numerous quintiles for a comprehensive analysis. Moreover, since PQR models an entire conditional distribution, it allows for an exploration of the effects of I.V. on the D.V. simply because the quintiles show a diverse set of effects in an individual conditional distribution. A PQR analysis also examines hidden heterogeneity across all cross-sections and assesses the slope coefficients for different quantiles corresponding to the various cross-sections (Amin et al., 2020). Additionally, decision-makers should keep in mind the value of the coefficient at the level of the distribution.

Table 10 has been placed as a second choice or robustness check estimator. The results in the quintiles show the effect of green finance and green technology innovation on CO_2 emission (EP). The quintiles for green finance are negative and statistically significant which determines that with green finance initiatives in cities in China, the amount of CO_2 emission is reduced which contributes to the environmental quality of China. All quintiles regarding GF are statistically significant. Likewise, the results in numerous quintiles for green technology innovation on CO_2 emission (EP). The quintiles for green finance are negative and statistically significant and also show statistically significant coefficients with negative signs which confirm the negative impact of GTI on CO_2 emission, implying that an increase in green technology innovation on CO_2 emission (EP). The quintiles for green finance are negative and statistically significant leading to an improvement in Environmental Performance.

Tabel 11 the heterogeneity was assessed based on dividing the firms in the Eastern region and Central and Western regions firms. Our results displayed that terms of both green finance and green technology innovation are some how same in both panels, i.e., eastern region, Central and western regions or cities as both green finance and green technology innovation reduce CO_2 emission which indicates that both regions in regards to its cities contribute to the regional environmental quality. Hence it is assumed and obtained that there are favoring results for both green finance and green technology innovation in both regional penal documents that heterogeneity does not exist in our data. The results are some how same in both panels for the Eastern region and Central and Western regions, which documented that there is no such bigger issue of heterogeneity in the data of these firms. Hence, our results would have no spurious coefficients.

5 Discussion based on the results

The findings of the study revealed that green financial performance has a negative impact on CO_2 emission which means that GF enhances environmental quality. While exploring the paradox of these kinds of

TABLE 7 Cointegration test.

Test	With. Outbreak	*p*–value	Mean shift	*p*–value	Regime shift	*p*–value
Explained. Variable: EP						
$Z\varphi(N)$	−6.983***	0.000	−5.834***	0.000	−5.217***	0.000
$Z\tau(N)$	−6.894***	0.000	−5.392***	0.000	−5.734***	0.000

TABLE 8 CS-ARDL long and short-run analysis.

Long-run analysis			
Variables	Co-efficient	t-stat	Prob
Explained variable: EP			
GF	−0.681***	−4.169	0.001
GTI	−0.645***	−2.685	0.001
CSD-statistics	0.000	0.032	0.609
Short-run analysis			
GF	−0.689***	−5.295	0.000
GTI	−2.054***	−6.049	0.000
ECT (−1)	−0.229***	−2.701	0.006

variables, Ji and Zhang (2019) also validated the efforts of firms to enhance their growth through green initiatives, as these initiatives bolster the environmental performance of the country by mitigating the adverse impact of CO_2 emission. The study supports the implementation of green instruments like green bonds and green loans, which serve to enhance and advance environmental sustainability efforts. Likewise, Falcone and Sica (2019), also validated that financial institutions can play a significant role in bolstering the financial capacity of small and medium-size businesses by offering green finance facilities. This, in turn, enables these businesses to effectively tackle challenges related to carbon dioxide emissions and mitigate the adverse effects of environmental degradation on the economy. Furthermore, the research conducted by JinRu and Qamruzzaman (2022) revealed that green finance has the potential to bolster environmental performance within an economy. According to the results obtained from the research conducted, it has been demonstrated that the performance of green technologies is possitively correlated with the performance of the environment due to its negative impact on CO_2 emission meaning that green practices and renewable energy reduce CO_2 emissions (Rehman et al., 2021b). In addition, Chege and Wang (2020) pointed out that green technology innovation has a positive impact on environmental performance. Zhang et al., 2022a also argued that green technology innovations can be vital to enhancing environmental quality. Likewise, Pofoura et al. (2021) argued

TABLE 9 Panel quantile regression results.

	GF		GTI		Constant	
Quantiles	Coefficient	S. Error	Coefficient	S. Error	Coefficient	S. Error
0.1	−1.356***	0.086	−0.546***	0.063	−5.602***	1.828
0.2	−1.331***	0.096	−0.563***	0.063	−6.130***	1.104
0.3	−1.617***	0.125	−0.493***	0.125	−6.678***	1.197
0.4	−1.308***	0.177	−0.536***	0.243	−5.133*	2.544
0.5	−1.467***	0.198	−0.851***	0.285	−3.094	5.056
0.6	−1.476***	0.236	−1.096***	0.315	7.541	5.818
0.7	−1.260***	0.196	−1.023***	0.233	12.289*	6.050
0.8	−1.239***	0.158	−1.016***	0.220	12.956**	5.163
0.9	−1.233***	0.128	−1.018***	0.148	15.522***	4.192

TABLE 10 Quantile regression robustness check.

	GF		GTI		Constant	
Quantile	Coefficient	S. Error	Coefficient	S. Error	Coefficient	S. Error
0.1	1.140*	0.519	−0.848***	0.219	1.980	3.791
0.2	1.783***	0.191	−0.411***	0.109	−6.110**	2.419
0.3	1.888***	0.239	−0.559***	0.111	−4.604	3.901
0.4	1.542***	0.271	−0.483***	0.091	−0.734	4.059
0.5	1.197***	0.259	−0.521***	0.061	7.631	5.161
0.6	1.187***	0.251	−0.488***	0.045	9.698*	5.051
0.7	1.321***	0.219	−0.444***	0.119	12.900***	3.389
0.8	0.992***	0.271	−0.356***	0.089	10.277***	2.441
0.9	1.281***	0.219	−0.449***	0.071	12.756***	3.059

TABLE 11 Regional heterogeneity.

	Model-1 Eastern region. CO_2	Model-2 Central and western regions. CO_2
G.F	−0.213**	−0.234**
GTI	−0.361**	−0.424***
Year Fixed Year	Yes	Yes
Adj- R^2	0.362	0.461

that green business practices help in reducing CO_2 emissions. Through the use of efficient technologies, energy transition, eco-friendly raw materials, and green human resources management, an organization with green technology innovation can overcome the problems associated with environmental degradation. Furthermore, Raihan (2023) also highlighted that in countries where industrialization is growing, rapid technological modernization contributes to increasing energy efficiency that improve the sustainability of the environment.

6 Conclusion

Due to intense efforts for the attainment of environmental milestones, countries like China also emphasize achieving environmental heights. This ambition has made China enhance greener practices. Hence we explored the impact of green finance and green technology on environmental performance, using green finance instruments in the form of indexes, i.e., green credit, green securities, green investments, and green loans, on the different firms in different cities' environmental performance. Our findings proved that green financial instruments are very effective in achieving environmental milestones in different cities, hence one of our hypotheses is achieved which means the accomplishment of one of our study objectives. This notion proved that green initiatives in Chinese cities turn the environmental quality table in favor of environmental regulatory bodies. Our results also validated the importance of green technology in bolstering the Chinese environmental performance at both central and western cities firms as well as industry levels that resultantly help in the quality environment, hence our second hypothesis and corresponding objective is achieved regarding the relationship between Green Technology Innovation and Environmental Performance. Thus our study proved that green finance and green technologies are considerably important due to their impactful contribution to the environmental performance of numerous cities resultantly improve the Chinese environmental quality. This notion proved to achieve the objectives of our study.

Based on the findings, it is advised that the financial institutions in China located in different cities should extend the services and volume of green services to the industrial units as well as households to assist the bodies involved in the concerned tasks of achieving city-level environmental quality. Chinese city-level administration should draw certain parameters for the industries and reward system to enhance the arsenals of greener practices. Moreover, due to the significant impact of green technologies in Chinese cities, the government should focus on investment in green technologies to obtain green output efficiency and green environmental milestones as these would directly impact the eco-friendly economic milestones of China. The environmental regulatory bodies should reward banks for providing green loans and consistently put their robust share in the Chinese green strategic framework. Firms should be encouraged and help out in the transition to green technology to enhance green total factor productivity. Certain limitations were witnessed in the data span for green finance parameters and greener technology as green finance is a very new emerging trend in the developing world.

Studies in the future should explore separate panels of at least the top ten cities of China to identify the magnitude of difference in terms of these variables' relationship and also make separate industry-level panels in these cities to conduct a robust and comprehensive study. Moreover, polluted and non-polluted firms should also be assessed in similar future studies.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

LJ: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Supervision, Software, Visualization, Project administration, Writing–original draft. MZ: Conceptualization, Formal Analysis, Investigation, Resources, Supervision, Writing–original draft, Methodology, Validation, Writing–review and editing, Visualization. AR: Conceptualization, Methodology, Data-curation, Formal-analysis, Funding-acquisition, Validation, Investigation, Software, Visualization, Writing–review and editing. KU: Conceptualization, Supervision, Methodology, Formal-analysis, Validation, Investigation, Funding-acquisition, Supervision, Software, Resources, Writing–review and editing.

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Is carbon trading working for construction companies green development ? Evidence from listed Chinese companies

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This study investigates the impact of China's carbon emission trading (CET) framework on the green development of the construction sector, a topic that has been underexplored. Utilizing annual data from 107 publicly listed construction companies from 2007 to 2022, we apply green total factor productivity (GTFP) as a metric for green development. Our findings reveal that GTFP increased by 0.36 during this period. Using the Difference-in-Differences (DID) methodology, we account for factors such as market dimensions, ownership structure, financial stability, geographical location, and state financial aid. The interaction term coefficient in our model is 0.0089, significant at the 1% level, indicating that CET implementation has significantly improved GTFP in construction enterprises. Heterogeneity analysis further shows that the CET's impact is more pronounced in large-scale, state-owned, highly indebted enterprises, those located in the eastern region, and those receiving government subsidies, with coefficients of 0.112, 0.0108, 0.0092, 0.0133, and 0.0099, respectively, all significant at the 1% level. These results underscore the importance of unified market development and tailored governance strategies. The study concludes with policy recommendations and calls for further research to explore CET's nuanced impacts across different sectors and regions.

KEYWORDS

construction firms, carbon emission trading, green development, difference-in-differences model, green total factor productivity

1 Introduction

The imperative to reduce emissions has become increasingly urgent as the climate continues to deteriorate. The Global State of Buildings and Construction Report 2022 reveals that carbon dioxide emissions from building operations surged to an unprecedented 10 billion tonnes in 2021, representing an increase over 2020 levels and surpassing the previous peak recorded in 2019 (Bahman et al., 2023). Consequently, the construction industry must integrate considerations of its ecological footprint into its operational frameworks, necessitating a transition towards low-carbon and sustainable development practices. There exists substantial potential for synergy between green development, corporate sustainability, and ecological resilience (Qin, 2023). Therefore, elevating the green development levels of construction enterprises has emerged as a pivotal issue in shifting from traditional production methodologies to sustainable long-term development within the industry.

Scholars have extensively studied methodologies to assess the degree of enterprises' green development. Some have pursued quantitative assessment approaches through the

construction of indicator measurement systems. For example, Wang et al. (2021) developed a comprehensive dark green evaluation index system for mineral resource listed companies, focusing on economic, environmental, and health perspectives. They identified managerial weaknesses and operational inefficiencies by evaluating enterprises' green development statuses. Yang and Fang (2020) introduced the concepts of carbon dioxide and green credit indices to measure unexpected and green outputs of real estate enterprises, conducting both static and dynamic evaluations of their green productivity. Helman et al. (2023) identified critical green metrics pertinent to the automotive industry, particularly focusing on elements during a vehicle's life cycle and potential data sources. Unlike the aforementioned studies, other scholars have approached the issue through qualitative analysis, focusing on developing theoretical frameworks and conceptual models for deeper examination. For instance, Tong and Zhang (2017) uses the external presentation layer, business support layer, and core layer to further explain the relationship between the green development capability of enterprises and suppliers, consumers, and the public, which improves the theoretical system of green development capability of enterprises. Ding and Yang (2019) establishes a green development reporting framework and green development indicators, and applies them to a case study of a Chinese textile enterprise, which provides a reference path for the enterprise to self-check and compare itself, and improve its own green development level. However, the application of these indicators lacks breadth, and it is difficult to circulate and use them in different evaluation calibres, which is insufficient to achieve intuitive comparison between different industries, regions and individuals. Green total factor productivity (GTFP), however, as a widely used green economic growth evaluation index has strong universality and comparability. The green development of enterprises is essentially the continuous improvement of GTFP, so this paper will use GTFP to measure the level of green development. Previous research on GTFP has mostly used econometric approaches to investigate the impact of economic and non-economic factors, as well as the interaction of input and output components. To realize enterprise green transformation, Chinese government has implemented carbon emission trading (CET) policy, which triggers a huge influence on various sectors. These policies also provide experiences for other economies to consider.

CET scheme aims to achieve emission reduction targets through a market-based approach. Within the framework of CET, emission quotas are established and allocated to participants through various mechanisms (Wang S. et al., 2022). Participants who emit less carbon dioxide than their allocated quota can trade surplus allowances in the market. Consequently, CET is recognized as a cost-effective mechanism for reducing emissions (Wang X. Q. et al., 2022). The Chinese carbon commercial market comprises eight percent of the global carbon market, amounting to approximately 4.5 billion tons (Zhang, 2022). This statistic highlights the extensive scope of China's carbon trading system and its significant impact on the nation's economic and societal structures. The building industry in China is markedly more energy-intensive compared to other sectors. Carbon emissions from the construction sector have been escalating, reaching approximately 2.1 billion tons in 2019, thus constituting a substantial proportion of the nation's total emissions. This figure represents a threefold increase from the 2000 level of 668 million tons, reflecting a consistent annual growth rate of 6.96% (Bahman et al., 2023). Therefore, analyzing the impact of CET on green development through Green Total Factor Productivity (GTFP) is imperative for construction firms. This research is pivotal for advancing the building industry towards sustainability and efficiency within the global CET system.

GTFP, encompassing economic development, energy consumption, and environmental degradation, has become a critical indicator for academics studying corporate carbon reduction transitions and green development levels (Li et al., 2022). GTFP extends the traditional concept of Total Factor Productivity (TFP) by incorporating environmental elements to assess the efficiency of corporate inputs and outputs (Zhou et al., 2023). Firms adopting this methodology acknowledge that economic prosperity should not come at the expense of the environment, thereby promoting sustainable and ecologically conscious advancement (Zhang et al., 2021). Researchers have identified several significant drivers of GTFP, including digital twin technology (Hao et al., 2023), remote development (Jian et al., 2023), artificial intelligence (Ying et al., 2023), the industry agglomeration effect (Cheng and Jin, 2022), and ecosystem protection (Cheng and Kong, 2022). Although these studies have explored the primary factors affecting GTFP, they have predominantly focused on the industry as a whole, neglecting the crucial role of construction enterprises in the carbon emission reduction market. Furthermore, these investigations have not adequately aligned their findings with current carbon emission reduction strategies. This study examines the impact of the Carbon Emissions Trading (CET) policy on construction companies' GTFP, utilizing a Difference-in-Differences (DID) model on construction firms listed from 2007 to 2022. The research aims to elucidate how CET improves construction enterprises' GTFP through empirical testing and additional analysis of its various roles. It aspires to guide China's construction industry towards a sustainable development path that balances economic growth with environmental sustainability, energy efficiency, and emission reduction, while also providing significant insights for global counterparts pursuing green development.

In the context of enhancing corporate green development, numerous scholars have engaged in extensive discussions and research. These studies are concentrated in the following areas. First, system design has emerged as the most direct means for scholars to improve corporate green development. For instance, Xiong et al. (2023) investigated the impact and heterogeneity of establishing green standards on corporate green development. Aragòn-Correa et al. (2020), DeLaPaz (2013) and Vierra, (2016) found that both mandatory and recommended standards can guide companies in formulating their strategic plans and self-assessment goals, significantly advancing green development through the promotion of green innovation dissemination. Second, financial instruments, due to their close relationship with economy entity, have become vital in encouraging companies to improve their green development levels. Several research indicates that green financial products provide economic support for companies to adopt green practices, thereby promoting greater willingness among companies to engage in green behaviors. In terms of technological innovation in construction companies, new green building materials and creative

designs aligned with sustainable development principles offer critical green elements to their products, ensuring that corporate planning is not merely theoretical. Additionally, some scholars have explored the role of green organizational culture and green knowledge management in enhancing employees' green creativity, further driving corporate green development. Jiang et al. (2020a) developed an employee green creativity scale from four dimensions: green creative motivation, thinking, behavior, and outcome, to promote green development from the perspective of enhancing employees' green creativity. Wang S. et al. (2022) demonstrated that green knowledge management enhances an organization's capacity for green innovation and achieving sustainable development goals.

However, the current research gap lies in the fact that these studies focus on companies across various industries without specific data and circumstances for any particular sector. Although scholars like Jiang et al. (2022) have investigated the socio-economic and environmental effects of incorporating high oil-consuming and natural gas industries into the carbon emissions trading system, there is a significant gap in research on construction enterprises characterized by high energy consumption and long project cycles. This makes it challenging for managers and policymakers in the construction industry to obtain effective guidance when formulating green development strategies. Therefore, there is a lack of comprehensive and effective post-evaluation mechanisms to ensure the effective implementation and continuous improvement of green production measures. The aim of this paper is to fill this research gap.

As previously mentioned, research on the green development levels of construction enterprises is currently very limited. Thus, the primary contribution of this study is its targeted use of data from the construction sector, focusing on analyzing the impact of the CET policy on construction enterprises. This avoids the pitfall of analyzing the entire industry while ignoring sector-specific characteristics. Secondly, this study innovatively explores the green development direction of construction enterprises from the perspective of the post-implementation effects of the policy. This research not only provides policymakers with a framework for analyzing the construction industry but also offers industry managers a mechanism for self-evaluation. Thirdly, as the world's largest developing country, China's issues and solutions regarding the green development of its construction enterprises offer valuable insights for all other developing countries and regions. Other developing countries facing similar issues can adopt this study's theoretical framework, combined with their own circumstances, to further explore the green development levels of local construction enterprises and the implementation of the CET policy. Lastly, the heterogeneity analysis in this study further examines the reactions of different types of construction enterprises to the CET policy, deeply integrating the characteristics of construction enterprises and addressing the often-overlooked issue of how to enhance their green development levels.

The remainder of this study is structured as follows. Section 2 outlines the related work including key factors, methodology and research hypotheses as well as model construction. Section 3 describes the model results. Section 4 shows the tests of robustness. Section 5 proposes the mechanism test. Section 6 demonstrates the heterogeneity analysis. Finally, Section 7 summaries the conclusions and policy recommendations.

2 The related work

2.1 The significance of CET policy for building companies green development

Carbon trading policy, being a prominent environmental regulatory instruments, has emerged as the primary mechanism for encouraging the transition to sustainable practices in construction firms. China's CET policy has garnered substantial practical insights throughout its execution and is poised to supplant the EU Emissions Trading System (ETS) as the world's largest carbon market. Consequently, an examination of China's carbon trading landscape stands to enhance the global understanding of carbon trading mechanisms in developing nations. This development has triggered a surge of scholarly research aimed at evaluating the efficacy of CET policies, with numerous academics analyzing CET through the lenses of macroeconomics and public policy design (Dong et al., 2013; Zhao et al., 2016; Munnings et al., 2016).

Studying the impact of CET policy on the green development of construction enterprises has become imperative for promoting sustainability in the construction industry. In the carbon emission regimes of Europe and the United States, specific carbon-emitting devices or facilities have become the focus of their rules (Zhang, 2015). In contrast to the CET frameworks in western countries, China's CET policy mainly focus economic entities such as enterprises rather than specific devices. Consequently, utilizing enterprise data to analyze China's CET market represents a prevailing approach in contemporary research. This approach not only aids policymakers in comprehending CET policy implementation but also enables construction company managers to gain a clearer insight into their economic standing and future strategic endeavors.

Consequently, attaining a thorough comprehension of the influence of CET policies on the sustainable growth of construction enterprises, elucidating the primary regulators and mediating factors, and evaluating policy responses across diverse scenarios are imperative for advancing the sustainability agenda within the construction sector. This approach not only facilitates the progression towards eco-friendly practices but also contributes to the enhancement of the global carbon trading framework's theoretical underpinnings. The outcomes of such investigations offer a spectrum of strategies aimed at bolstering the efficacy of carbon trading markets in developing nations.

2.1.1 Measurement of GTFP

Initial economic development theories, including the Solow growth model and the endogenous growth model, posited that sustainability relied solely on technological advancement, as indicated by Total Factor Productivity (TFP). However, these models failed to take into account the larger socioeconomic advantages of resource exploitation as well as environmental factors (Chen and Golley, 2014). With energy and environmental limits increasingly hampering economic growth, the oversight became apparent when production resources needed to be redirected to environmental management activities, slowing economic advancement (Liu et al., 2020). The Asian Productivity Organization introduced the concept of GTFP in the 1990s to

address this issue by supporting a holistic strategy that increases productivity while also promoting environmental stewardship. Subsequent research has focused on methods for evaluating green productivity growth in order to more properly assess economic sustainability (Liu et al., 2020). In this setting, studies concentrating on GTFP indicators that account for energy and environmental performance have increased, emphasizing their importance. Xia and Xu (2020) used GTFP to analyze the quality of China's economic growth, revealing disparities between GTFP and traditional TFP measurements that exclude environmental concerns, with certain northeastern areas outperforming and others in the western region behind. Additional research looked into the factors that drive China's green productivity growth, focusing on the effects of economic scale, structure, technological advancement, and innovation. Further research has examined the impact of governmental policies and regulatory systems on green productivity. Providing essential insights for understanding variances in green productivity and instructing policymakers on how to promote green economic advancement.

In the measurement of GTFP, scholars have engaged in explorations, leading to two main controversies. Firstly, there is debate on how to appropriately incorporate environmental factors into the production function. In 1983 Pittman was among the first to consider environmental pollution factors in economic models by accounting for pollution costs and integrating them into product prices for analysis (Tyteca, 1996). Färe (1989), Chung et al. (1997) applied directional distance functions (DDF) to estimate green TFP, incorporating environmental pollution emissions as an "undesirable output" into the model, a method widely acknowledged (Chung et al., 1997). Subsequently, Zhao et al. (2020) attempted to consider environmental pollution emissions, previously regarded as "undesirable output," as an input factor similar to capital and labor. Scheel, (2001) recalculated environmental pollution values by taking their reciprocal and incorporating them into the model, converting "undesirable output" into "desirable output." However, both approaches by Scheel, (2001) is contradictory to the actual production process of enterprises. Secondly, controversy exists regarding the methods used to calculate the final efficiency values after constructing production function models considering undesirable outputs. Reviewing the extant literature suggests that major estimating approaches now include: 1) The Solow residual method, akin to conventional TFP estimation, derives from Solow's growth theory. Hu et al. (2022) applied this technique to assess green TFP across various Chinese regions. 2) The nonparametric frontier analysis approach, as utilized by Feng et al. (2018), is prevalent for GTFP estimation, emphasizing the relative efficiency of inputs and outputs. Additionally, Tao et al. (2016) introduced an innovative Slacks-Based Measure (SBM) model that incorporates undesirable outputs, offering a novel methodology for evaluating green economic efficiency. Nonetheless, it is crucial to emphasize that this method is best suited for static assessments and does not capture the productivity dynamics of Decision-Making Units (DMUs) throughout multiple years. In contrast, incorporating unwanted outputs into the Malmquist-Luenberger (ML) index allows for a more precise measurement of DMU productivity improvements over time. Li and Chen (2021) created the SBM-ML model, which combines the SBM technique with unwanted outputs and a fixed ML index to precisely determine the extent of GTFP. This methodology combines nonparametric frontier analysis and the Malmquist-Luenberger index to provide a comprehensive tool for analysis. Researchers such as Wu et al. (2023) and Sun et al. (2021) have applied above approach to explore the basic operational mechanisms of green development in a company. Through studying previous research process, we calculated GTFP by appling SBM-ML model.

It is noteworthy that the academic community has identified indices similar to GTFP, namely, the Green Technology Efficiency Change Index (GTECI) and the Green Technology Progress Change Index (GTPCI). The GTECI assesses variations in the efficiency of factor utilization. This index is comprehensive, encompassing both the efficiency improvements brought about by technological advancements and the changes in efficiency due to the reallocation of production factors. Moreover, this index captures changes in economies of scale resulting from institutional innovation and the accumulation of experience within enterprises (Zhong, C et al., 2024). The GTECI is calculated primarily by comparing the production efficiency of different enterprises or units at a specific point in time. While, GTPCI measures the extent of technological advancement within a specific field or industry. It reflects the degree of innovation and development in technology, serving as an essential tool for evaluating the speed and direction of technological progress. The GTPCI is typically calculated by comparing changes in specific technological indicators over different time periods (Luo, Q., et al., 2019). In this study, we employed the growth rate method to compute this index, which involves calculating the growth rate of a particular technological indicator between two points in time. This research introduces the aforementioned indices to assist in analyzing the green development levels of construction enterprises over the past 15 years.

2.1.2 SBM – ML model

DMU, which functions at the minimum level of production, refers to the separated listed firms in the database of this research. Assume there are DMUs, represented by DMU_j $(j = 1, 2, \ldots, n)$. Each DMU utilizes m inputs, symbolized by x_i $(i = 1, 2, \ldots, m)$; q_i and produces pollution as an output, denoted by y_r $(r = 1, 2, \ldots, q_1)$; q_2 (pollution output), denoted as b_t $(t = 1, 2, \ldots, q_2)$. The DMU under evaluation is denoted as DMU_0. Following the aforementioned conceptualization, we derive the following SBM model incorporating pollution output:

$$
\begin{aligned}
\min \rho = & \frac{1-\frac{1}{m}\sum_{i=1}^{m} s_i^- \Big/ x_{i0}}{1+\frac{1}{q_1+q_2}\left(\sum_{r=1}^{q_1} s_r^+ \Big/ y_{r0}+\sum_{t=1}^{q_2} s_t^{b-} \Big/ b_{t0}\right)} \\
\text{s.t. } & \sum_{j=1}^{n} x_{ij}\lambda_j + s_i^- = x_{i0}, \quad i = 1, 2, \cdots, m \\
& \sum_{j=1}^{n} b_{tj}\lambda_j + s_t^{b-} = b_{t0}, \quad t = 1, 2, \cdots, q_2 \\
& \sum_{j=1}^{n} \lambda_j = 1 \\
& \lambda, s^-, s^+, s^{b-} \geq 0
\end{aligned}
\tag{1}
$$

In Eq. 1, $(\sum_{j=1}^{n} \lambda = 1)$ refers to returns to scale (RS). Removing this restriction implies fixed returns to scale (FRS). This study primarily focuses on efficiency in the context of RS. The suitable countermeasures to the preceding equation is denoted as $(\lambda^*, \&s^{-*}, \&s^{+*}, \&s^{b*})$. When accounting for undesirable outputs, the DMU_0 is meaningful only when ρ^*equals one, in other words, s^{-*}, s^{+*} and s^{b*} are all tantamount to zero.

2.1.3 Malmquist indicator

Malmquist index was devised by Sten Malmquist in 1953. Subsequently, Chung et al. (1997) modified this model to create the ML index, which extends the Malmquist framework to encompass undesirable outputs through the directional distance function. Any Malmquist index that accounts for unwanted outputs will now be referred to as the ML productivity index, or simply the ML indicator. The ML indicator developed as follows:

The collection of reference for the unit duration is denoted by $S^f = \left\{\left(x_j^f, y_j^f, b_j^f\right)\right\}$ with f representing the number of observations in period 1. Given that the efficient production possibility frontier per unit period remains unchanged, a singular ML index is computed.

$$ML_0^f\left(x_0^{t+1}, y_0^{t+1}, b_0^{t+1}, x_0^t, y_0^t, b_0^t\right)) = E_0^f\left(x_0^{t+1}, y_0^{t+1}, b_0^{t+1}\right) / E_0^f\left(x_0^t, y_0^t, b_0^t\right) \quad (2)$$

The DMU0 flux from duration t to t + 1 is denoted as $ML_0^f\left(x_0^{t+1}, y_0^{t+1}, b_0^{t+1}, x_0^t, y_0^t, b_0^t\right)$. Among them, $E_0^f\left(x_0^t, y_0^t, b_0^t\right)$ and $E_0^f\left(x_0^{t+1}, y_0^{t+1}, b_0^{t+1}\right)$ stands for the utility values of DMU_0 in t and t + 1 duration regarding the efficient production possibility frontier constructed by period f. $ML_0^f\left(x_0^{t+1}, \&y_0^{t+1}, \&b_0^{t+1}, \&x_0^t, \&y_0^t, \&b_0^t\right) = 1$ indicates that TFP remains fixed, $ML_0^f\left(x_0^{t+1}, \&y_0^{t+1}, \&b_0^{t+1}, \&x_0^t, \&y_0^t, \&b_0^t\right) > 1$ demonstrates that TFP rises, and $ML_0^f\left(x_0^{t+1}, \&y_0^{t+1}, \&b_0^{t+1}, \&x_0^t, \&y_0^t, \&b_0^t\right) < 1$ represents that TFP falls. This study does not focus on the deep decomposition of the indicator, but simply on the indicator itself.

Calculated steps:

In this study, we employ the method developed by Li and Chen's (2021) to determine the green development efficiency value for the base period, designating 2007 as the baseline year. The GTFP of a listed firm in a specific period, relevant to the initial duration (the starting time in the dataset under inquiry), can be seen as below:

$$E_0^1\left(x_0^t, \&y_0^t, \&b_0^t\right) = E_0^1\left(x_0^1, \&y_0^1, \&b_0^1\right) \times ML_0^1\left(x_0^2, \&y_0^2, \&b_0^2, \&x_0^1, \&y_0^1, \&b_0^1\right) \times \ldots \times ML_0^1\left(x_0^t, \&y_0^t, \&b_0^t, \&x_0^{t-1}, \&y_0^{t-1}, \&b_0^{t-1}\right) \quad (3)$$

By putting Eq. 2 into Eq. 3, we show that the both sides of the equation are identical. As a result, Eq. 3 calculates the GTFP for all listed firms compared to the base period. This enables for a thorough comparison of these organizations' productivity, both horizontally and vertically.

2.1.4 Calculation result

Based on the above, this study calculates the GTFP, GTECI, and GTPCI of Chinese listed construction enterprises from 2007 to 2022. Due to the large number of specific enterprises involved, we averaged the values for each year to obtain the annual average values for all listed construction enterprises, thereby studying the overall green development situation of the enterprises. The specific values are shown in Table 1. Figure 1 illustrates the trend changes of the three indices from 2007 to 2022. Figure 1 indicates that the trends of GTFP and GTECI are largely consistent. Both indices increased from 0.74 to 1.15. This data shows that from 2007 to 2022, the GTFP of listed construction enterprises in China rose by 41%. Notably, following the implementation of the CET policy in 2013, the GTFP increased by 24%.

TABLE 1 The annual average value of GTFP, GTECI, and GTPCI of listed construction companies in China from 2007 to 2022.

Year	GTFP	GTECI	GTPCI
2007	0.739087432	0.736542813	1.003584033
2008	0.767337049	0.761912396	1.007332395
2009	0.795097927	0.792081428	1.00404582
2010	0.823647226	0.819551226	1.00520733
2011	0.851791467	0.845346667	1.007839449
2012	0.875010202	0.876582538	0.998285866
2013	0.907250417	0.904673258	1.003113205
2014	0.927896705	0.934246882	0.99336166
2015	0.960144086	0.957783054	1.002595692
2016	0.979317368	0.984619355	0.994815146
2017	1.009877204	1.012408163	0.99767648
2018	1.039450529	1.04026283	0.999456534
2019	1.062875974	1.064611768	0.998609304
2020	1.092182022	1.092054366	1.000297862
2021	1.117939329	1.122550022	0.996040937
2022	1.15136	1.150559381	1.000857849

In contrast, the increase from 2007 to 2013 was 16.8%. To investigate whether this rapid increase is attributable to the CET policy, this study proposes a hypothesis and will establish a model for verification. Over the past 15 years, the GTPCI has remained relatively unchanged, consistently maintaining a value of 1. This indicates that there have been no significant breakthroughs in innovation related to green production technologies and processes in the Chinese listed construction industry over this period. This phenomenon warrants the attention of both industry professionals and government authorities.

2.2 Research hypotheses

2.2.1 Factors affecting green development level of building companies

Based on the literature review of previous studies, this research identifies the key factors influencing corporate green development and uses them as research variables in the foundational model. Various types of construction firms, each facing unique circumstances, exhibit varying levels of effectiveness in engaging with CET mechanisms. Jiang H. D et al. (2020) in their study elaborated that assessing environmental policies requires a combination of multiple factors, therefore this study will refer to the previous results to continue to assess the impact of CET policies on the level of green development of construction firms from a multifactorial perspective. More specifically, Li et al. (2022) posits that larger firms possess greater financial resilience, enabling them to navigate the financial demands of green transitions effectively and enhance their sustainability practices swiftly. In terms of shareholding structure, Hua et al. (2022) highlights state-owned enterprises' (SOEs) notable social responsibility compared to private enterprises, as they often collaborate closely with local governments in China,

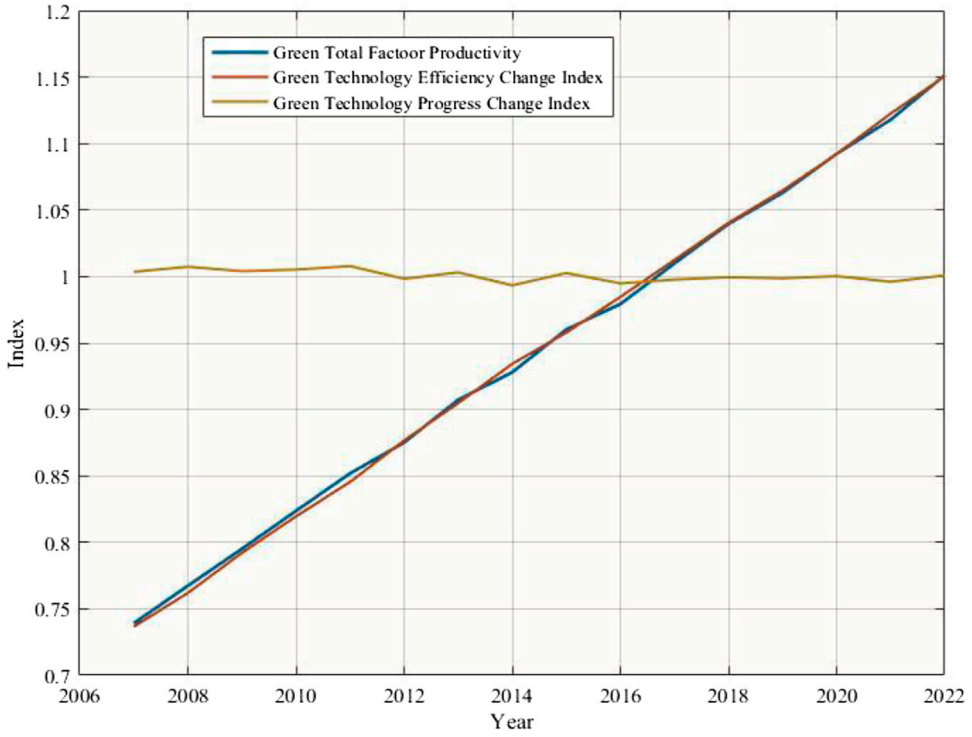


FIGURE 1
Development trend of GTFP, GTECI, and GTPC from 2007–2022.

demonstrating proactive commitment to green initiatives. In addition, financial considerations are indispensable for a business. Alonso-Martinez et al. (2021) underscores the role of green credit in supporting firms to implement sustainable business models, expediting their transition towards sustainability. Moreover, Chen Y et al. (2017) underscores the significance of subsidies in aiding enterprises to navigate transition periods, regain stability, and enhance their eco-friendly practices. Jiang et al. (2024) in his research emphasized that subsidies for renewable energy represent a relatively optimal approach to achieving green development, demonstrating the critical role of subsidies in enhancing levels of green development. Furthermore, technological innovation has garnered attention from numerous researchers. Gomes et al. (2024) emphasizes the pivotal role of green innovation in driving enterprises towards higher levels of environmental responsibility. Jiang et al. (2023) provides a detailed description of the characteristics of the agricultural sector, evaluates the impacts of different technological scenarios under the carbon reduction background on agricultural development, and emphasizes the influence of technological innovation on green transformation. Specifically, Jiang et al. (2020b) pointed out that carbon capture and storage technologies are crucial technologies in current green development. It is worth noting that China's vast territory results in significant heterogeneity in carbon emissions reduction and green development levels across different regions, as evidenced in Jiang H. D. et al.'s (2023) study.

In summary, based on previous scholars' utilization of factors influencing environmental policies and green development levels, this study selected enterprise size, ownership structure, debt levels, geographic location, subsidy acceptance, and technological innovation as influencing factors. Subsequently, it explores the development of green development levels among construction enterprises following their participation in the CET policy.

2.2.2 Theoretical hypotheses on the relationship between CET and GTFP

Carbon emission market prices internalize the external costs associated with construction enterprises' carbon emissions, allowing for effective management of carbon emissions throughout production and operational activities. This regulation is largely assisted by cost drivers and profit incentives. Cost drivers refer to the commercialization of carbon emission rights, which is closely regulated by government bodies. Under such regulatory regimes, building businesses that need to emit more than their given quotas must get additional emission rights from the government or the market. This acquisition leads in additional environmental maintenance charges, which reduces the firm's GTFP to some extent. Enterprises that fail to comply with environmental standards will suffer equivalent fines, raising their additional expenses and requiring all building enterprises to efficiently use carbon emission limits. Profit incentives are primarily expressed in the ability of carbon emissions rights to be sold within a specific market mechanism, hence enabling profit potential for participating firms. Using this strategy, construction companies can reduce carbon emissions through increased technical innovation while also collecting revenue by exchanging excess quotas. Specifically, if the expense incurred by a company to cut emissions falls below the prevailing carbon market

rate, it has the opportunity to sell its surplus carbon emission allowances on a trading platform, profiting from the margin between expenditure of maintenance and sale price. This incentive mechanism implies that the better an enterprise's efficiency in technological innovation, the cheaper its emission-reduction expenses and the higher its earnings from carbon trading. Carbon emission quotas are efficiently dispersed using market trading methods, resulting in lower carbon emissions and cheaper costs for all participating enterprises. Consequently, this research proposes Hypothesis 1 concerning the effectiveness of CET policies.

Hypothesis 1. Pilot carbon emissions trading policies enhance GTFP in construction enterprises.

2.2.3 Theoretical hypotheses of green innovation in CET and GTFP of construction firms

Scientific and technological advancements are critical for increasing organizations' GTFP. Within the scope of designated carbon emission quotas, construction enterprises in pilot carbon emissions trading regions are increasingly focusing on developing emission reduction technology. This priority intends to minimize emission costs and increase efficiency, hence accelerating research into emissions-reducing technology, ultimately lowering prices and improving the effectiveness of carbon emission reduction activities. In contrast, building companies produce excess carbon emission quotas by implementing novel green emission reduction solutions. These excesses can then be traded on the carbon trading market, creating new opportunities for profit. From a strategic, long-term standpoint, the most effective way for construction enterprises to negotiate carbon emission regulations and minimize emission costs is to vigorously develop and implement carbon emission reduction technology. Given this circumstance, construction companies are actively involved in green innovation research and development in the context of carbon trading policies. Such occurrences not only ensure that the construction industry's overall carbon emissions meet government-imposed emission constraints, but they also spark a wave of research into new carbon emission reduction technologies across the industry, thereby improving the GTFP of all industry enterprises. To study this, the paper looks at the path of green innovation and the conduction mechanism. Hypothesis 2 is provided to demonstrate that carbon emissions trading pilot regulations improve the GTFP of construction firms in pilot areas by encouraging enterprise innovation.

Hypothesis 2. Carbon emissions trading pilot policies drive enterprise innovation, increasing construction firms' GTFP.

2.3 Model construction

The Difference-in-differences (DID) method is popular in econometrics and quantitative analysis. This study employs the DID approach to ascertain the influence of CET on the green development level of construction companies. DID has the advantage of being applicable to large-sample regressions and representing trends more accurately within huge datasets. This study includes data from 1,040 publicly traded construction companies, meeting the criteria for massive data situation. In management sciences, this approach employs observational data to replicate experimental research by comparing the effects of an intervention on a "treated group" to those on a "control group" within a quasi-experimental framework. This technique evaluates the effect of an intervention by analyzing and comparing the baseline characteristics or time-related changes during the output variable between the therapeutic and containment groups. Prior to conducting DID analysis, the time-series data for both groups must cover at least two periods: one before and one following the intervention. This method is extensively used to evaluate treatments or interventions including legislative passing, policy enactment, and mega project implementation.

The research framework of this article is structured as follows (see Figure2): First, the collected data is cleaned, and key research variables are extracted. Second, a basic model is established, and multicollinearity tests are conducted. Only models that pass the multicollinearity tests, confirming the absence of linear relationships among variables, proceed to the next stage of analysis. Third, conducting rigorous robustness tests on the basic model is essential to ensure the scientific validity of the analysis results. Therefore, parallel trend tests, placebo tests, propensity score matching, and mechanism tests will further evaluate the model's reliability. Models that fail these tests will be redesigned until they meet the required standards. Finally, a heterogeneity analysis will be conducted to deeply examine the research results. As Figure 1 illustrated, this study analyzes the impact of CET policies on the green development level of construction enterprises based on market scale, ownership structure, financial structure, geographic location, and government subsidies.

2.3.1 Description of variables

The sample of the study is the construction industry with a time horizon of 2007–2022 years, 107 companies with 15 years of annual data and a sample size of 1,029 observations were used in this study. The analysis tool is Stata 17.0.

For the dependent variables, GTFP is assessed using the non-radial SBM-ML index. Drawing on existing literature, we identified factors potentially influencing the GTFP of construction firms and chose the following as control variables to mitigate estimation bias: Firm market scale (Scale), Return on assets (Roa), Gearing ratio (Lev), agency cost (Cost), cash flow from operations (CF), factor intensity (Capital), and the shareholding ratio of the largest shareholder (Top1). The definitions of these variables are provided in Table 2.

2.3.2 Construction of baseline model

To assess the influence of CET on the GTFP of construction businesses, the following model was developed for this study (see Eqs 4, 5):

$$\begin{aligned} GTFP_{i,t} = {} & \alpha_0 + \beta_1\ DID_{i,t} + \beta_2\ Size_{i,t} + \beta_3\ ROA_{i,t} + \beta_4\ Lev_{i,t} \\ & + \beta_5\ Cost_{i,t} + \beta_6\ CF_{i,t} + \beta_7\ Capital_{i,t} + \beta_8\ Top1_{i,t} \\ & + \delta_t + \mu_i + \varepsilon_{i,t} \end{aligned} \tag{4}$$

To verify the presence of the mechanism effect, the subsequent model was developed as follows:

$$\begin{aligned} GTFP_{i,t} = {} & \alpha_0 + \beta_1\ DID \times Patent_{i,t} + \beta_2\ DID_{i,t} + \beta_3\ Patent_{i,t} \\ & + \beta_4\ Size_{i,t} + \beta_5\ ROA_{i,t} \end{aligned} \tag{5}$$

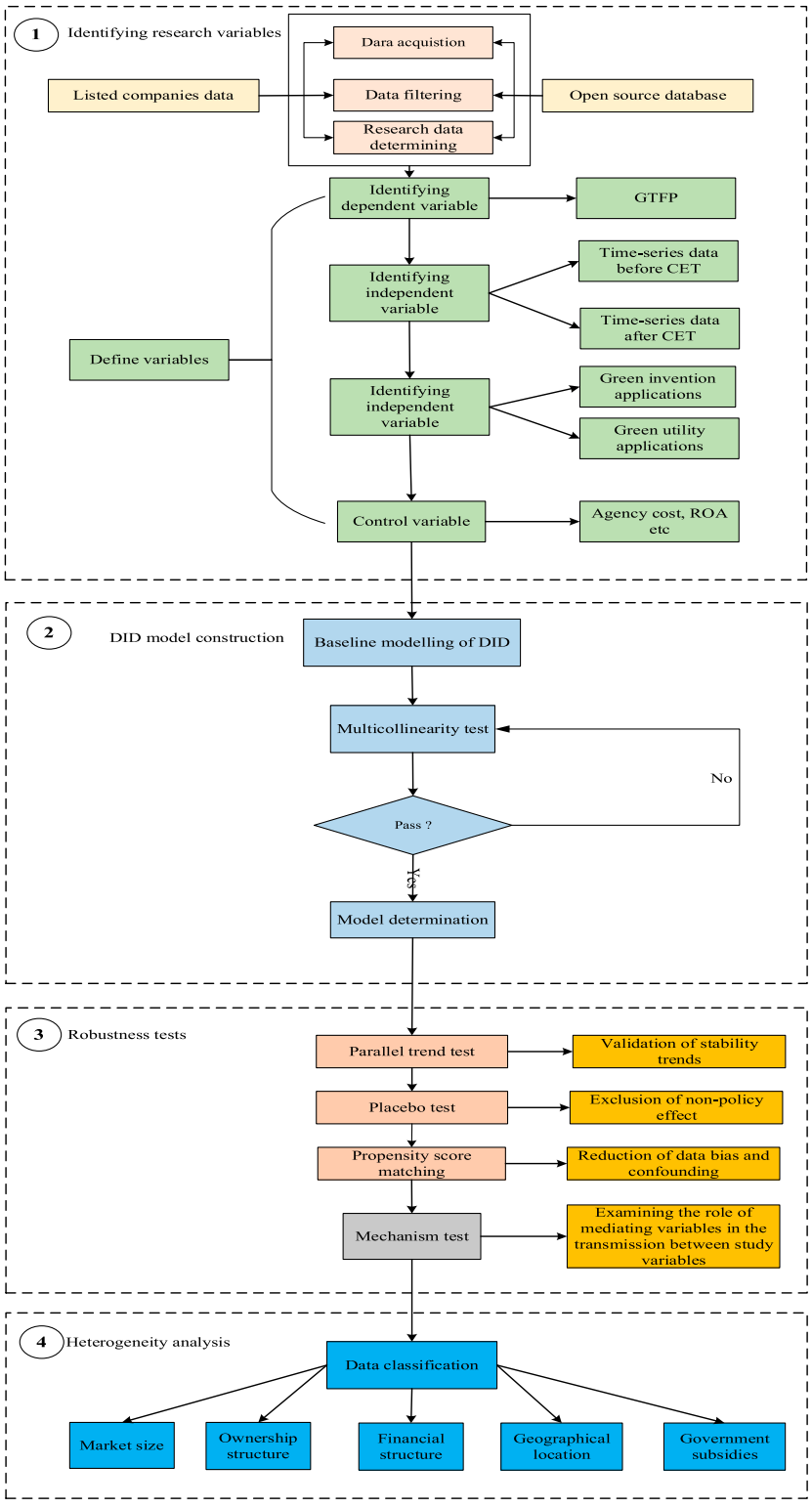


FIGURE 2
Research framework.

$GTFP_{i,t}$ refers to the GTFP of the construction firms of sample i in the observation duration t, α stands for the constant term, and β refers to model coefficient of unit variable. If β is a positive number, the GTFP of the building companies affected by CET is markedly stronger than those not affected by CET. It indicates that CET increases the GTFP of the building companies. DID

TABLE 2 Definitions of variables.

Variable symbol	Name	Description
GTFP	Green total factor productivity	Measured by non-radial SBM-ML index
DID	Double-difference interaction term	Treat * Post
Scale	Firm market scale	Ln (Sum assets in final duration)
ROA	Return on assets	Net profit
Lev	Gearing proportion	Total liabilities
Cost	Agency fees	Executive management expenditure/Main operating revenues
CF	Cash flow during the period of operation	Net cash flow during operation/end-of-period total assets
Capital	Elements Concentration	Ln (Actual net fixed assets unit capital)
Top1	Shareholding proportion of the Highest shareholder	Shareholding proportion of the Highest shareholder
GreInv	Enterprise Invention Green Innovation	Ln (the quantity of patent applications for green invention)
GreUm	Enterprise Practical Green Invention	Ln (the quantity of patent applications for Green utility model

represents the interaction term Treat $_{i*}$ Time $_{t}$, reflecting the treatment effect's average difference in GTFP between construction enterprises impacted by the CET scheme and those not affected. The "Treat" group signifies the policy treatment dummy variable (for pilot areas such as Beijing, Tianjin, Shanghai, Guangdong, Shenzhen, Hubei, Chongqing), "Treat" is 1; for non-pilot areas, "Treat" is 0. "Post" denotes period virtual variable (1 after CET implementation, 0 in front of, with 2013 designated as the policy year). In this study, Patent $_{i,t}$ is connected to green creation level of firms, reflecting the quantity of green innovations and utility applications. The time effect (δ_t) is measured in the temporal dimension, while the fixed effect (μ_i) is measured in the unit entrepreneurial level. The random disturbance term ($\varepsilon_{i,t}$) changes in both entrepreneurial and time.

3 Analysis of empirical research

3.1 Sample selection and database

The listed corporate data is notable for its accessibility and correctness. Furthermore, data from publicly traded construction enterprises, often collected from their standardized annual reports, aids scientific research.

This study encompassed construction firms that are listed on the Shanghai Stock Exchanges and Shenzhen Stock Exchanges and adhere to construction sector classification guidelines established by the China Securities Regulatory Commission. Selected firms were involved in a range of sectors including property, urban street construction, engineering raw materials, and other citizens' welfare infrastructure development corporation (to name a few facilities for culture, education, health, sports, and music), as well as monumental architecture and various other construction activities. The research assessed the effects of CET, green innovation, and GTFP on the civil engineering and construction sectors, utilizing annual data spanning from 2007 to 2022. The dataset was preprocessed and cleaned before being analyzed. Out of 1,728 construction firms, 699 were removed because they did not fit the study's criteria, leaving 1,029 useable observations. The mentioned construction enterprises' financials and quantity of green patents were collected from China National Research Data Services (CNRDS) (https://www.cnrds.com/) (accessed on 10 October 2023) and national patent databases (https://english.cnipa.gov.cn/index.html). The analysis used Stata 17.0's "opreg" command, China stock market and accounting research database (www.gtarsc.com) (accessed on 11 August 2023). Supplementary data sources were Tonghuashun (https://www.10jqka.com.cn/; an information website of stock) and Finance of Sina (https://finance.sina.com.cn/). The focal variable, green creation, was quantified through the tally of green invention application and utility model application, indicative of technological progress. Data on green patent application were collected from China National Intellectual Property Administration (english.cnipa.gov.cn/) (accessed on 13 August 2023), categorized using green patent classification of world intellectual property organization (www.wipo.int/portal/en/index.html) (accessed on 15 August 2023) totally green invention applications. A linkage was identified between the quantity of green inventions and green creation level. The study encompassed 150,994 green invention patents and 20,389 green practically model applications. All of the above data is consolidated in the following links: https://github.com/Kriscoo/research-data-and-code-of-construction-companies-green-development.

Table 3 indicates a description of the statistics for key factors. Table 2 shows that the mean, minimum, and maximum GTFP values for construction enterprises are, and 1.146, respectively, with a standard deviation of 0.113, indicating significant variation and data dispersion. The mean quantity of green patents and practically applications unit firm stands at 1.06 and 1.273, respectively, with standard deviations being 1.377 and 1.422.

3.2 Multicollinearity test

Multicollinearity occurs when the explanatory variables in a regression model exhibit strong or precise relationships, resulting in

TABLE 3 Descriptive statistics.

	N	Mean	SD	Min	Median	Max
GTFP	1,029	0.968	0.113	0.712	0.988	1.146
DID	1,029	0.423	0.494	0	0	1
Scale	1,029	22.881	1.803	16.185	22.522	28.502
ROA	1,029	0.015	0.076	−0.986	0.022	0.502
Lev	1,029	0.642	0.189	0.028	0.674	1.89
Cost	1,029	0.064	0.097	0.001	0.044	1.404
CF	1,029	−0.002	0.366	−11.056	0.012	0.43
Capital	1,029	12.012	1.148	4.431	12.047	15.386
Top1	1,029	0.375	0.151	0.044	0.358	0.786
GreInv	1,029	1.06	1.377	0	0.693	6.513
GreUm	1,029	1.273	1.422	0	0.693	6.234

TABLE 4 Calculation of variance inflation factor.

Variables	VIF	1/VIF
Scale	1.860	0.537
Lev	1.560	0.641
Top1	1.180	0.850
Cost	1.169	0.854
ROA	1.159	0.864
DID	1.130	0.883
Capital	1.059	0.942
CF	1.031	0.970
Mean VIF	1.269	

skewed or difficult-to-estimate outcomes. As for this study, we used the approach of Variance Inflation Factor (VIF) to assess the model for multicollinearity, with the goal of identifying and addressing any flaws. Significant multicollinearity is defined as a maximum VIF value greater than 10 (Kim, 2019). When all VIF values are less than 10, the model is considered to be free of multicollinearity. Multicollinearity reduces the dependability of model estimations, rendering the results questionable. Table 4 of this study demonstrates the absence of multicollinearity, as all VIF values are below 10. Therefore, this model does not suffer from multicollinearity.

3.3 Consequence of basic model analysis

The outcomes of basic regression models employed in this research are presented in Table below. In column (1) of Table 5, excluding control variables yet incorporating bidirectional fixation effects, exhibits a modulus of 0.0093, and it is statistically significant at the 1 percentage level. In second Column, which contains control variables but no fixed effects, has a coefficient of 0.0850, which is likewise substantially positive at the 1% level. The model displayed in third column, incorporating control variables and bidirectional fixation effects, yields a coefficient of 0.0089, statistically remarkable at the level of 1 percent. This denotes an impressive rise in GTFP for laboratory group, specifically an increase of 0.0089 units. Among the control variables, with all else constant, the coefficient for Lev is significantly positive, signifying a meaningful positive impact of Lev on GTFP. These findings suggests that CET policy may positively influence construction enterprises' GTFP, providing preliminary support for Hypothesis 1. To increase the confidence of these findings, the study will perform a number of robustness checks. Moreover, the values for the models in Table 4 exceed 0.1, deemed an acceptable level of explanatory power given the complexity of the researched phenomena.

4 Test of robustness

4.1 Test of parallel trend

Employing DID method necessitates the parallel trends assumption, which posits that before realization of CET policy in 2013, experimental group's data should align with the control group's across various indicators, exhibiting parallel trajectories. If this criteria is not met, the DID model may be ineffective, resulting in biased results. To test for parallel trends, this study develops a regression equation using dummy variables, as shown below:

$$\begin{aligned} GTFP_{i,t} = {} & \alpha_0 + \beta_1 Pre_{i,t} + \beta_2 Pre_{i,t} + \beta_3 Pre_{i,t} + \beta_4 Current_{i,t} \\ & + \beta_5 Post1_{i,t} + \beta_6 Post2_{i,t} + \beta_7 Post3_{i,t} + \beta_8 Size_{i,t} \\ & + \beta_9 ROA_{i,t} + \beta_{10} Lev_{i,t} + \beta_{11} Cost_{i,t} + \beta_{12} CF_{i,t} \\ & + \beta_{13} Capital_{i,t} \end{aligned} \quad (6)$$

In the specified Eq. 6, $Pr3_{i,t}$ denotes the status of company "i" in period "t" as being in the third year prior to the implementation of the CET pilot policy. The assignment of the variable is 1 when companies are in third year prior to the policy's implementation, and 0 otherwise. "$post1_{i,t}$" signifies company "i" in period "t" as being in the first year following the import of CET policy, with variables set to 1 for companies in the first year post-impact and 0 otherwise. "$current_{i,t}$" represents company "i" in period "t" during the ongoing influence of CET pilot policy, with the assignment of the variable is 1 when companies is currently being influenced and 0 otherwise. The other variables remain consistent with those applied in the regression analysis.

In Table 6, the first column is evident that coefficients are not significant in Pre $3_{i,t}$, while the coefficients from Post current $_{i,t}$ to Post $3_{i,t}$ are obviously positive. It suggest that there are no significant differences between the laboratory group and controlled groups before realization of CET policy, corroborating the parallel trends hypothesis. Furthermore, the CET pilot strategy has shown effective in increasing GTFP among construction enterprises, albeit with some delay in its implementation. Overall, the study's research design complies with the preconditions for applying the DID approach.

Visualizing the parallel trends test results, as shown in Figure 3, before and during the current period (such as, before the policy is implemented), demonstrates no remarkable differences in the

TABLE 5 The outcomes of basic regression models.

Variables	(1) GTFP	(2) GTFP	(3) GTFP
DID	0.0093*** (0.0023)	0.0850*** (0.0065)	0.0089*** (0.0023)
Scale		0.0174*** (0.0023)	−0.0004 (0.0011)
ROA		−0.2188*** (0.0427)	0.0088 (0.0074)
Lev		−0.0222 (0.0198)	0.0168*** (0.0047)
Cost		−0.0346 (0.0335)	0.0018 (0.0062)
CF		0.0054 (0.0083)	0.0017 (0.0015)
Capital		−0.0107*** (0.0027)	−0.0003 (0.0006)
Top1		−0.1331*** (0.0215)	0.0027 (0.0079)
Constant	0.7399*** (0.0026)	0.7326*** (0.0510)	0.7416*** (0.0222)
Observations	1,029	1,029	1,029
R-squared	0.9804	0.2818	0.9807
Number of id	107	107	107
Firm	yes	no	yes
Year	yes	no	yes
F value	3021***	50.02***	2082***

Standard errors in parentheses.
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

TABLE 6 The parallel trends results.

Variables	(1) GTFP
pre_3	−0.0067 (0.0045)
pre_2	−0.0068 (0.0041)
pre_1	−0.0051 (0.0042)
current	−0.0052 (0.0035)
post_1	0.0071** (0.0035)
post_2	0.0092** (0.0045)
post_3	0.0087** (0.0039)
Scale	−0.0009 (0.0008)
ROA	0.0095* (0.0051)
Lev	0.0178*** (0.0036)
Cost	0.0015 (0.0048)
CF	0.0021*** (0.0007)
Capital	−0.0003 (0.0007)
Top1	−0.0011 (0.0072)
Constant	0.7531*** (0.0191)
Observations	1,029
Number of id	107
R-squared	0.9809
Firm	yes
Year	yes
F value	2243***

Standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

dependent variable between controlled group and laboratory group. This result remains true even after accounting for control parameters such as Scale, ROA, Lev, Cost, CF, Capital, and Top1, all of which have confidence intervals that contain zero. This supports the parallel trend assumption. After the policy's implementation, the lower limits of the modulus intervals for prior three periods are strictly above zero, suggesting that CET had a remarkable catalytic effect on GTFP.

4.2 Test of placebo

The goal of placebo tests is to determine whether a policy or intervention actually caused the desired outcome. These tests are used to rule out the possibility of other unobserved factors influencing the findings, hence confirming the causality of the study's conclusions. In the field of economics, placebo tests are employed to exclude the impact of non-policy factors on the study results. For example, if a policy is about to be implemented, it may affect the behavior and outcomes of the subjects under study, leading to errors in the so-called "policy effect." Placebo tests help ascertain whether the policy is indeed the cause of the observed results.

To ensure the dependability of experimental research findings, this work follows Topalova's (2010) methodology and employs a counterfactual testing approach for placebo tests. This entails changing the policy implementation dates in the sample data to 2009 and 2010—years before the actual carbon trading policy pilotand running regression analyses. If the carbon pricing policy pilot in 2013 had increased construction companies' GTFP, the interaction term coefficients for these hypothetical pilot years should produce insignificant findings. As illustrated in columns (1) and (2) of Table 7, DID2009 and DID2010 are scenarios in which CET pilot policy is assumed to have been implemented in 2009 and 2010, respectively. The insignificance of the interaction term coefficients for both DID2009 and DID2010 confirms that the improvement non GTFP among construction enterprises is due to the carbon pricing pilot policy adopted in 2013. This data reinforces the notion that the carbon trading pilot scheme notably improved the GTFP of construction firms.

4.3 Propensity score matching

Studies indicate that CET pilot strategy enhances GTFP of construction businesses. Yet, these figures do not sufficiently depict the causal link between CET and GTFP of construction firms. Furthermore, business size and investment in technological development have a considerable impact on construction firms' GTFP. To confirm that the rise in GTFP attributed to the carbon trading pilot policy is not accidental, it is essential to account for confounding factors like business size. As a result, this study uses propensity score matching to address sample selection bias, reducing disruptions to experimental outcomes and increasing

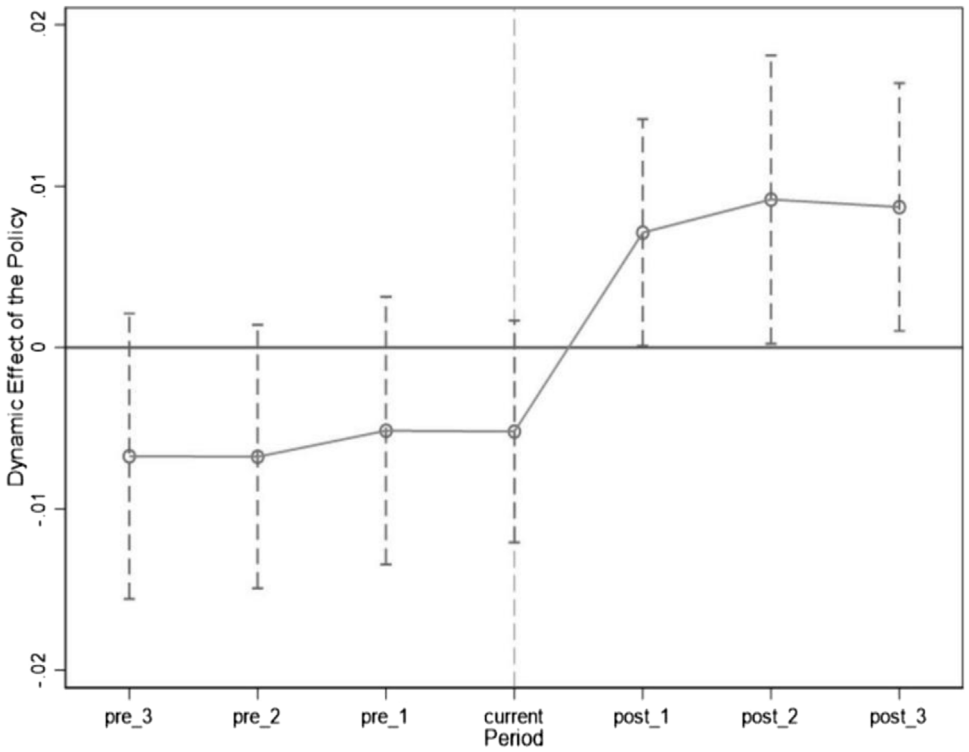


FIGURE 3
Visualization of parallel trend test results.

the study's robustness. Table 8 presents the methods of kernel, nearest neighbor and radius matching. The consistency in the sign and significant level of DID coefficients of interaction term with prior analyses suggests that the regression outcomes are robust. This reinforces previous regression findings that the carbon pricing pilot scheme significantly enhances GTFP in construction firms.

4.4 Explanatory variables in one-period

In fourth column of Table 8 explores potential lagged effect of CET by analyzing key explanatory elements in subsequent duration, as denoted by the modulus L.DID. The data demonstrate that regression modulus consistently remain significantly positive, suggesting the robustness of basic regression outcomes.

5 Mechanism test

Previous research has shown that by implementing CET pilot programs, building businesses' GTFP can improve dramatically. Building on this insight, some researchers believe that green technical breakthroughs aiming at reducing carbon emissions can have a significant impact on GTFP oscillations. Building on this foundation, the present research examines green technological innovation as a possible mediating factor, employing a mediation effect model to analyze the influence of CET on construction businesses' GTFP. The coefficient in first column of Table 9 pertains to the coefficient with quantity of green patent applications DID_{Inv}, showcasing a significantly positive coefficient (0.0027). It can been seen that the quantity of patent applications for green utility model (DID_{Um}) exerts an advancing effect on the connection between DID and GTFP. Similarly, in second column, the interaction coefficient relates to the quantity of GreUm by construction firms, with a coefficient of 0.0026, also significantly positive. This reveals that GreUm positively moderates the connection between DID and GTFP. These data imply that by focusing on green innovation technologies, construction enterprises can increase their GTFP.

6 Heterogeneity analysis

6.1 Market scale perspectives

Construction companies market scale significantly affects equivalent of carbon emissions to be reduced and associated maintenance expense. This study assesses whether CET's impact on construction firms' GTFP significantly differs by company size, with firms classified according to size in the database. Separate basic regressions are performed for larger and smaller firms. Regression outcomes presented in the first and second columns of Table 10 indicate that the CET pilot positively influences the GTFP of larger-scale construction enterprises by 1%, while it has no discernible effect on smaller-scale entities. This suggests that CET has a stronger influence on larger enterprises than on smaller ones. This gap may be ascribed to major construction businesses' greater risk-management

TABLE 7 Test result of placebo.

Variables	(1)	(2)
	GTFP (DID 2009)	GTFP (DID 2010)
DID2009	0.0044	
	(0.0040)	
DID2010		0.0052
		(0.0033)
Scale	−0.0008	−0.0008
	(0.0011)	(0.0011)
ROA	0.0099	0.0095
	(0.0075)	(0.0074)
Lev	0.0181***	0.0179***
	(0.0047)	(0.0047)
Cost	0.0012	0.0008
	(0.0063)	(0.0063)
CF	0.0015	0.0015
	(0.0015)	(0.0015)
Capital	−0.0003	−0.0003
	(0.0006)	(0.0006)
Top1	−0.0018	−0.0009
	(0.0078)	(0.0079)
Constant	0.7497***	0.7488***
	(0.0223)	(0.0223)
Observations	1,029	1,029
R-squared	0.9804	0.9805
Number of id	107	107
Firm	yes	yes
Year	yes	yes
F value	2,051***	2,054***

Standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

capabilities. In the context of new policy implementation, large construction enterprises can use their established industrial chains, strategic relationships, and economies of scale to offset market risks. They leverage their long-established market share, reputation, and influence to do so. It is noteworthy that large construction firms, due to their more significant social influence, are more likely to receive government financial subsidies and tax incentives. They can use national macro policies to pave their way toward autonomous transformation. For deep analysis, Large-scale enterprises experience a faster increase in GTFP compared to small-scale enterprises. The primary reasons for this phenomenon are as follows: Firstly, enterprises of different market sizes have varying resource integration capabilities. Large construction enterprises, leveraging their superior resource integration capabilities, can more effectively spread fixed costs. Specifically, large construction enterprises can attract significant investments in environmental technology and establish industry-influential innovation and research platforms. This conclusion is confirmed by Zhou et al. (2023), who also highlight that large enterprises have greater bargaining power in this process, giving them an advantage in reducing costs. Consequently, in the carbon trading market, they can more easily absorb and internalize carbon costs, thereby improving GTFP. Secondly, large construction enterprises typically develop more mature risk management systems and higher resilience as they grow. This enables them to better manage uncertainties and price fluctuations in the carbon trading market, swiftly adjusting strategies to respond to market changes. This ability results in higher policy response capabilities for large enterprises, particularly those with dedicated policy research and response departments. These enterprises can promptly interpret and respond to government environmental policies and regulations. Not only can they quickly adjust their operational strategies, but they can also influence policy direction through lobbying and participation in policy formulation, making policies more favorable to their development. This is substantiated by the research of Kalaycıoğlu et al. (2016). Thirdly, larger enterprises place greater emphasis on social responsibility and brand image construction. By participating in the carbon trading market, they not only enhance their GTFP but also improve their social reputation and brand value. This positive feedback mechanism further promotes their advancement in green development levels. This finding is supported by Yang et al. (2016).

6.2 Enterprise ownership perspectives

Construction firms may differ in their societal roles depending on whether they are state-controlled. This is particularly evident in the differences between stateowned enterprises (SOEs) and privately-owned enterprises (POEs). The existence of such differences leads to varying responses and outcomes in relation to the government's CET pilot policy among firms of different ownership types. This study uses a dummy variable to characterize firm ownership, separating the sample into SOEs and non-state-owned enterprises, and doing a DID analysis on them. Table 10's third and fourth columns reveal that state-owned construction enterprises' GTFP has a substantial favorable impact (interaction term coefficient = 0.0108, $p < 1\%$). Conversely, the interaction term coefficient for private construction businesses is 0.0092, demonstrating statistically significant at one percentage level. This indicates that the coefficients for SOEs are slightly elevated compared to those for non-SOEs, with SOEs also exhibiting a higher level of significance. This suggests that while the policy impacts both firm types, its effect is more pronounced on SOEs, signifying that government-implemented CET programs exert a stronger influence on state-owned entities than on private firms. SOEs tend to achieve faster green development under the CET policy for several reasons: Firstly, according to government intervention theory, state-owned construction enterprises are subject to stronger government supervision and policy guidance. This oversight ensures a certain level of efficiency and consistency

TABLE 8 Potential lagged effect results for CET.

Variables	(1)	(2)	(3)	(4)
	GTFP (kernel)	GTFP (neighbor)	GTFP (radius)	GTFP
DID	0.0090***	0.0107***	0.0089***	
	(0.0024)	(0.0038)	(0.0023)	
L.DID				0.0111***
				(0.0022)
Scale	−0.0002	0.0001	−0.0004	−0.0002
	(0.0011)	(0.0017)	(0.0011)	(0.0010)
ROA	0.0092	0.0139	0.0088	0.0117
	(0.0095)	(0.0170)	(0.0074)	(0.0073)
Lev	0.0169***	0.0094	0.0168***	0.0149***
	(0.0055)	(0.0096)	(0.0047)	(0.0048)
Cost	0.0023	0.0056	0.0018	0.0012
	(0.0077)	(0.0099)	(0.0062)	(0.0060)
CF	0.0106	0.0262**	0.0017	0.0016
	(0.0077)	(0.0122)	(0.0015)	(0.0014)
Capital	−0.0003	−0.0005	−0.0003	−0.0006
	(0.0006)	(0.0010)	(0.0006)	(0.0006)
Top1	0.0036	−0.0115	0.0027	0.0076
	(0.0082)	(0.0130)	(0.0079)	(0.0078)
Constant	0.7358***	0.7404***	0.7416***	1.1102***
	(0.0240)	(0.0354)	(0.0222)	(0.0239)
Observations	1,022	527	1,029	922
R-squared	0.9804	0.9783	0.9807	0.9811
Number of id	107	102	107	98
Firm	yes	yes	yes	yes
Year	yes	yes	yes	yes
F value	2,033***	823.9***	2,082***	1,986***

Standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

in executing national policies. Due to government ownership, SOEs must balance shareholder interests with the government's social and economic objectives, providing greater motivation to implement carbon reduction policies (Zhu et al., 2016). Secondly, compared to private enterprises, state-owned construction enterprises enjoy better social recognition and reputation in securing financing and technical support. This advantage facilitates more effective participation in carbon trading markets and investment in clean technologies. Additionally, SOEs typically have long-term development strategies and a stronger sense of social responsibility, focusing not only on short-term profits but also on long-term sustainability and environmental protection. Most SOEs align their long-term plans with national strategic plans, which makes them more inclined to engage in carbon trading policies and actively reduce emissions. Lastly, SOEs often have strict organizational cultures and regulatory systems, ensuring greater compliance with carbon trading policies and reducing violations. Moreover, significant social and political pressures, along with a self-demonstration effect, drive SOEs to execute green transitions more rigorously and comprehensively.

6.3 Financial structure perspectives

Based on financial leverage theory, incurring debt could shrink the capital expenditure associated with conducting business operations, thereby aiding in the enhancement of a

TABLE 9 Mechanism test result.

Variables	(1) GTFP	(2) GTFP
DID_{Inv}	0.0027*** (0.0009)	
GreInv	−0.0016* (0.0009)	
DID_{Um}		0.0026*** (0.0009)
GreUm		−0.0002 (0.0009)
DID	0.0045 (0.0028)	0.0040 (0.0028)
Scale	−0.0002 (0.0011)	−0.0004 (0.0011)
ROA	0.0080 (0.0074)	0.0071 (0.0074)
Lev	0.0180*** (0.0047)	0.0182*** (0.0047)
Cost	0.0014 (0.0062)	0.0012 (0.0062)
CF	0.0015 (0.0015)	0.0017 (0.0015)
Capital	−0.0004	−0.0006
Top1	0.0032 (0.0079)	0.0032 (0.0078)
Constant	0.7363*** (0.0224)	0.7429*** (0.0227)
Observations	1,029	1,029
R-squared	0.9809	0.9810
Number of id	107	107
Firm	yes	yes
Year	yes	yes
F value	1923***	1930***

Standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

firm's profitability. For managers, a higher debt ratio means a greater concentration of equity, enabling shareholders to obtain a larger share of the profits from projects. This is particularly relevant in construction firms that have an appetite for risk, as an increased proportion of debt can lead to investments in higher-risk projects. This research categorizes construction firms into high and low debt groups based on their debt-to-asset ratio median values, conducting distinct regression analyses for each. The aim is to ascertain the differential impact of the CET program on companies with varied debt levels. As illustrated in Table 10's fifth and sixth columns, coefficient of construction firms regarding high level debt is notably significant in one percentage level, whereas for those in low level debt, it is remarkably significant with five percentage level. Moreover, the modulus for high level debt data are marginally bigger than that for the low level debt, suggesting a more pronounced level of significance. This demonstrates that the policy significantly impacts both groups, with notably higher efficiency for high-debt companies. This indicates that the CET policy exerts a remarkable influence on GTFP of construction companies with high level debt than those in low level. Such effect could be mainly attributed to the interpretation that a high debt ratio reflects a firm's optimism regarding its future profitability. Markets tend to favor working with such companies, which in turn can promote the enhancement of their GTFP. In addition, By analyzing previous research and incorporating the findings, it is evident that construction enterprises with high levels of debt may face significant financial pressure and a need for stringent cost control. Carbon trading policies offer the opportunity to generate additional revenue through emission reductions, which is particularly attractive to highly indebted enterprises. Consequently, these firms are likely to be more motivated to actively participate in carbon trading (Lu Y et al.).

6.4 Geographical location perspectives

Since China has a vast land, there are significant developmental gaps between its eastern and western regions, which are reflected in the construction industry's varying responses to the CET pilot policy. As a result, this study divides enterprises into three categories based on their geographical location: eastern, middle, and western. Table 11 presents the experimental data, including experimental consequence for different regions (eastern, middle, and western) in columns 1, 2, and 3, respectively. The results reveal that the policy effect is remarkable at one percentage level in the eastern region, whereas the consequence for middle and western area are not significant. The results indicates that policy's impact is more effective in the eastern rather than middle and western areas. The lack of significant interaction term coefficients for middle and western areas indicates that to be a new carbon emission reduction tool, CET, is more evident in well-developed areas. As for middle and western regions, still depending on traditional, energy-intensive construction processes and boasting less vibrant marketplaces, are not fully reaping the advantages of novel programs like CET.

6.5 Official subsides perspectives

Whether a firm receives government subsidies can impact its business operations to a certain extent. This study incorporates a dummy variable for government subsidies to assess the differences in policy effects for construction businesses that get them vs. those that do not. It splits the sample data into two groups: firms that receive government subsidies and those that do not, and then runs simple regression analysis on each. As depicted in columns 4 and 5 of Table 11, the interaction term coefficient for enterprises that receive government subsidies is remarkably positive in one percentage level. The consequence indicates a substantial policy effect on these subsidized businesses in advanced regions. This phenomenon may occur because construction firms that receive government subsidies can leverage this financial support to enhance their capacity for innovation and management. This can lead to continual improvement in their GTFP and promote overall corporate performance enhancement. This conclusion has been confirmed in the photovoltaic industry. Numerous scholars (Li et al., 2022) have found that subsidies, as a policy tool, have strongly promoted the development of emerging green industries. However, this significant impact is only evident in the early stages of the industry, with less noticeable effects during the intermediate and mature stages (Nordensvard et al., 2018; Wang Z. et al., 2018).

TABLE 10 Heterogeneity analysis result.

Variables	(1) (BigSize)	(2) GTFP (SmallSize)	(3) GTFP (State)	(4) GTFP (Private)	(5) GTFP (HighLev)	(6) GTFP (LowLev)
DID	0.0112*** (0.0042)	0.0052 (0.0040)	0.0108*** (0.0031)	0.0092** (0.0040)	0.0133*** (0.0034)	0.0100** (0.0040)
Scale	0.0012 (0.0023)	−0.0003 (0.0023)	−0.0005 (0.0018)	0.0009 (0.0025)	−0.0025 (0.0019)	0.0011 (0.0025)
ROA	0.0651** (0.0286)	0.0058 (0.0081)	0.0059 (0.0161)	0.0110 (0.0109)	0.0115 (0.0132)	0.0009 (0.0122)
Lev	0.0111 (0.0165)	0.0207*** (0.0064)	0.0136 (0.0090)	0.0141** (0.0071)	0.0161 (0.0104)	0.0219** (0.0100)
Cost	0.0233 (0.0250)	0.0016 (0.0070)	0.0065 (0.0107)	0.0010 (0.0097)	0.0004 (0.0112)	0.0030 (0.0108)
CF	0.0142 (0.0141)	0.0015 (0.0018)	0.0137 (0.0098)	0.0022 (0.0029)	0.0027* (0.0016)	0.0054 (0.0106)
Capital	−0.0017 (0.0015)	−0.0006 (0.0008)	−0.0027** (0.0013)	0.0004 (0.0008)	−0.0023 (0.0015)	−0.0003 (0.0009)
Top1	0.0080 (0.0120)	−0.0225 (0.0150)	0.0074 (0.0096)	0.0079 (0.0204)	0.0079 (0.0107)	−0.0129 (0.0167)
Constant	0.7097*** (0.0494)	0.7528*** (0.0453)	0.7697*** (0.0414)	0.7015*** (0.0538)	0.8009*** (0.0438)	0.7179*** (0.0514)
Observations	514	515	530	499	514	515
R-squared	0.9751	0.9693	0.9846	0.9726	0.9812	0.9727
Number of id	66	88	53	71	75	85
Firm	yes	yes	yes	yes	yes	yes
Year	yes	yes	yes	yes	yes	yes
F value	757.3***	580.4***	1320***	654***	986.9***	659.9***

Standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

TABLE 11 Heterogeneity analysis result.

Variables	(1) GTFP (East)	(2) GTFP (middle)	(3) GTFP (West)	(4) GTFP (YES)	(5) GTFP (NO)
DID	0.0078*** (0.0030)	0.0060 (0.0092)	−0.0006 (0.0064)	0.0099*** (0.0026)	−0.0234 (0.0222)
Scale	0.0001 (0.0012)	−0.0031 (0.0042)	0.0041* (0.0022)	−0.0006 (0.0011)	0.0051 (0.0144)
ROA	0.0095 (0.0079)	0.0136 (0.0334)	−0.0452 (0.0833)	0.00102 (0.0094)	−0.0239 (0.0363)
Lev	0.0148*** (0.0051)	0.0322 (0.0220)	−0.0041 (0.0167)	0.0182*** (0.0051)	−0.0314 (0.0450)
Cost	−0.0003 (0.0078)	0.0069 (0.0150)	0.0937 (0.0599)	0.0034 (0.0091)	−0.0076 (0.0262)
CF	0.0010 (0.0016)	0.0231 (0.0225)	0.0023 (0.0323)	0.0019 (0.0015)	0.0161 (0.0337)
Capital	−0.0000 (0.0015)	−0.0030 (0.0026)	−0.0035 (0.0028)	−0.0004 (0.0008)	0.0004 (0.0039)
Top1	0.0048 (0.0097)	−0.0141 (0.0274)	−0.0044 (0.0116)	0.0079 (0.0082)	−0.1563 (0.1411)
Constant	0.7261** (0.0251)	0.8277*** (0.0933)	0.6803*** (0.0452)	0.7483*** (0.0240)	0.7081*** (0.2992)
Observations	807	131	91	964	65
R-squared	0.9802	0.9855	0.9890	0.9787	0.9763
Number of id	84	13	10	107	25
Firm	yes	yes	yes	yes	yes
Year	yes	yes	yes	yes	yes
F value	1,575***	295.8***	262.9***	1,741***	50.31***

Standard errors in parentheses ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

7 Conclusion and policy recommendations

7.1 Conclusion

As global climate change worsens, carbon trading is increasingly recognized as a critical environmental management and control technique for mitigating the negative consequences of economic activity on the climate. Additionally, considering the vital role of the building industry in human survival, supporting green and sustainable development in this sector is critical to the existing economic and social framework. Thus, investigating the response of construction firms' green development situation to the implementation of CET policies is critical for their harmonious development. This research analyzes data from construction firms listed on the Shanghai and Shenzhen A-share and ChiNext markets between 2007 and 2022. It utilizes DID and mediation effect models to empirically explore the influence of CET on the green development situation of Chinese construction companies, aiming to elucidate the underlying mechanisms. The key finding is that the CET policy significantly enhances the GTFP of these firms. Additionally, green technology innovation serves as a pivotal mechanism through which CET policy influences the GTFP of these enterprises. According to the analysis, the carbon emissions pricing plan benefits larger-scale, state-owned, and deeply indebted construction businesses more. Furthermore, enterprises in China's eastern regions show a greater improvement in GTFP than those in the middle and western areas. This research indicates that CET could enhance the green development level of construction firms in China and it is necessary to adjust the policy according to different situation of firms.

7.2 Practical implications

Reflecting on and focusing on the implementation of CET policies in developed regions can provide valuable lessons for developing countries and regions. For example, the development of CET policies in the European Union has had different impacts on enterprises at different stages. Andreou and Kellard (2021) found that companies with proactive environmental behaviors under the EU ETS performed poorly financially. From the first to the second phase, the EU Emissions Trading System (ETS) harmed corporate profits (Abrell et al., 2011). In the third phase of the EU ETS, the motivation for companies to improve production efficiency may not have improved (Carratù et al., 2020). If the carbon emission trading system becomes more stringent, high-emission enterprises are more likely to divest and relocate (Genovese and Tvinnereim, 2019). Conversely, some scholars have found that companies participating in CET could pass the additional costs onto consumers through product pricing, leading to increased turnover (Marin et al., 2018). Regarding China's specific national conditions, construction enterprises transitioning from traditional operational models to green low-carbon models will inevitably incur costs, which will likely be borne by consumers (Zhang and Wang, 2021). Timely monitoring of the effects of construction enterprises participating in carbon trading policies is crucial for maintaining the effectiveness of these policies.

This study proposes an evaluation and impact tracking mechanism for the implementation of CET policies, establishing a post-evaluation framework and model for construction enterprises participating in carbon trading policies. Based on the results of this study, green innovation has a positive impact on enhancing the green development levels of construction enterprises. Therefore, government departments should implement incentive policies for green patent inventions and utility models or regularly hold invention competitions to stimulate technological innovation. For bidding units, adding green innovation as a criterion in standards can strengthen the requirements for green innovation among bidders. In corporate management practices, managers should establish green research departments and collaborate extensively with research institutions or research-oriented universities. This "enterprise-university-research institute" collaboration can achieve synergy and integration of functional and resource advantages, facilitating the alignment and coupling of upstream, midstream, and downstream technological innovations. Secondly, the green development levels in China's central and western regions lag significantly behind those in the eastern regions. Therefore, market regulators should avoid a one-size-fits-all approach when establishing national standards and promote a virtuous cycle in which the eastern region drives green development in the central and western regions. Thirdly, it is recommended that government departments establish driving and incentive mechanisms at the current stage. For example, during the bidding process, tendering units should be encouraged to set green development evaluation points, giving enterprises with higher green development levels a better chance of winning contracts. Additionally, this study finds that state-owned and government-subsidized construction enterprises show more significant improvements in green development levels when participating in CET policies. This suggests that government departments can have state-owned enterprises take on more leading responsibilities and provide appropriate subsidies to private construction enterprises to help them navigate crises. Finally, highly leveraged enterprises also exhibit significant improvements in green development levels. Therefore, in practice, banks and financial institutions should be encouraged to increase the issuance of green loans and financial derivatives to stimulate enterprises to raise their debt levels, thereby enhancing their green development levels.

7.3 Suggestion for CET policy

The Chinese CET market represents a multifaceted and systemic endeavor. Based on the findings of this study, it is clear that further enhancement in strategic planning, market structures, and subsidy frameworks is necessary within the national carbon market. Therefore, the following recommendations are proposed: First and foremost, enhancing the regulations and support mechanisms of the carbon trading market is essential to ensure that carbon quota trading occurs in a legal and structured manner in China. This approach will maximize the effectiveness of carbon pricing policies in improving firms' GTFP and assist construction companies in their transformation and upgrading efforts. The government should actively promote carbon trading plans to encourage voluntary compliance and foster a positive market environment. Additionally, participants in the carbon market should establish channels for green technology innovation and

increase their investment in scientific research and technological development. Government departments should utilize macroeconomic regulation to strengthen the market mechanism's incentive effect on innovative enterprises, creating policy tools that incentivize green innovation technology. This alignment will synchronize the influx of social capital with the financial needs of enterprises for research and development.

Furthermore, there should be a gradual enhancement of the carbon finance market mechanism to amplify the incentivizing effect of green finance on carbon trading entities. At present, China's national carbon financial market remains in its nascent phase, characterized by limited activity and public acceptance of pilot carbon financial product transactions. Consequently, China's carbon market development should explore the derivatives market, forming targeted financial tools to stimulate the active participation of construction companies in carbon trading and their sustainable transformation. In addition, the government should increase policy subsidies for construction companies. When these companies encounter challenges in their transformation or face existential threats, the government should provide support funds or tax incentives to bolster their risk mitigation capacity. Moreover, it is crucial to reduce the movement of carbon emissions between regions, which may result from differing regional subsidy schemes. The subsidy system should act as a catalyst for reducing carbon emissions. It is also vital to establish a platform for sharing exemplary practices, highlighting the leading role of large, state-owned enterprises, particularly those in the Eastern region, within the carbon trading market. Businesses in Central and Western China's less developed carbon markets could benefit from opportunities for learning and networking through rewards for exemplary cases and inter-regional conferences. This strategy will enhance the efficacy of green transformation across society.

Finally, it is imperative to implement differentiated environmental regulatory strategies tailored to the characteristics of construction enterprises in different regions of China, considering their varying sizes, ownership types, and debt levels. Avoiding a one-size-fits-all regulatory approach is necessary to ensure equitable treatment of different types of enterprises, fostering a fair competitive environment that maximizes the effectiveness of environmental regulations. Additionally, rapidly achieving the decoupling of high production capacity from high carbon emissions is a critical goal.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://github.com/Kriscoo/research-data-and-code-of-construction-companies-green-development.

Author contributions

JT: Writing–original draft. YL: Writing–review and editing. ML: Data curation, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Byte-Sized Finance, Bushel-Sized Benefits: unraveling digital financial inclusion impact on China's agricultural green development

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Introduction: China's rural financial landscape has long been characterized by exclusion, leaving countless farmers without access to essential financial services. However, the advent of digital financial inclusion presents a promising solution, offering low-cost, high-penetration avenues to bolster agricultural sustainability. This paper unravels how "Byte-Sized Finance" can yield "Bushel-Sized Benefits" in China's agricultural green development.

Methods: Methodologically, we pioneer a novel system to gauge agricultural green development across 31 Chinese provinces spanning from 2013 to 2021. Empirically, employing fixed-effect, mediation effect, and spatial Durbin models.

Results: Our study reveals the intricate pathways through which digital financial inclusion influences agricultural green development. We find that it exerts its impact through the lenses of industrial structure and entrepreneurship, operating at both macro and micro levels. Furthermore, our analysis uncovers spatial spillover effects, shedding light on the differential roles played by these mechanisms across regions.

Discussion: This groundbreaking discovery underscores the transformative potential of leveraging digital financial inclusion to propel China toward agricultural green development. By shedding light on these crucial dynamics, our findings offer insights for policymakers, researchers, and practitioners striving to foster sustainability within China's agricultural sector.

KEYWORDS

digital financial inclusion, agricultural green development, spatial spillovers, sustainable development, green agriculture

1 Introduction

In modern societies, the importance of an inclusive financial system cannot be overstated. Nevertheless, the inherent bias of capital favoring the affluent while excluding the less privileged has resulted in a stark disparity in financial services. A considerable concentration of high-quality financial resources in urban areas, large corporations, and affluent segments has led to the exclusion of rural regions, small and medium-sized enterprises (SMEs), and low-income groups (Leyshon and Thrift, 1993; Leyshon and Thrift, 1994; Leyshon and Thrift, 1995; Morrison and O'Brien, 2001; Leyshon et al., 2008). Scholars have extensively demonstrated the role of

financial development and financing behaviors in fostering sustainable economic, social, and environmental progress while curbing car-bon emissions (Scholtens and Dam, 2007; Shahbaz et al., 2013). However, global financial exclusion remains widespread (Demirgüç-Kunt et al., 2008). In 2012, the World Bank estimated that approximately 2.7 billion adults globally lacked access to formal financial services, particularly in impoverished rural households, where basic financial services are severely deficient (Koku, 2015; Khanal and Omobitan, 2020).

Agriculture, by its nature, is an environmentally sensitive industry, demanding significant investment and enduring lengthy harvest cycles. Yet, the adoption of green farming practices entails even greater costs. The traditional financial system has failed to meet the financing needs of farmers, necessitating a quest for new financial impetus to propel China's agricultural green development.

Financial inclusion and financial exclusion are different perspectives on the same issue. Alternatively, financial inclusion is needed precisely because of financial exclusion. Studies show that instability in the long-term development of finance is detrimental to the poor (Akhter and Daly, 2009; Wang et al., 2022b) and leads to increased income inequality (Altunbaş and Thornton, 2020; deHaan et al., 2023). Additionally, financial services are less accessible to poor residents (Ndlovu and Toerien, 2020; Alharbi et al., 2022). You et al. (2022) argue that regions with low economic growth are likely to face further disparity. The Pareto principle, as followed by the financial market, also raises the threshold of access for poor groups. According to a World Bank report (2018), nearly a third of adults were financially excluded, with their bank accounts not recorded in the official financial system. It was not until the advent of inclusive finance that new possibilities emerged for finance to truly serve a broader range of users.

The United Nations introduced the notion of inclusive finance in 2005 to facilitate the International Year of Microfinance. Inclusive finance is defined as a financial system that can efficiently and universally provide services to all levels and groups of society. The main goal of inclusive finance is to offer a wide range of financial services to society at an affordable cost, which is particularly significant for financially disadvantaged and poor groups. The initial form of inclusive finance was microfinance. After years of development, it now encompasses financial products and services such as credit, management, payment, insurance, and savings.

Recognizing the imperative for change, China has vigorously pursued its digital economy development strategy in recent years. Innovations in digital technologies, such as big data and cloud computing, have democratized access to financial resources, particularly in rural areas where resources and environments are more difficult, and facilitated a more equitable allocation of assets across critical sectors (Aziz and Naima, 2021).

In 2020, China achieved overall poverty alleviation with digital financial inclusion playing an essential role in this achievement. According to the "China Inclusive Finance Indicators Analysis Report (2020)" published by the Financial Consumer Rights Protection Bureau of the People's Bank of China and the "2020 Financial Institutions Loan Allocation Statistical Report" published by the People's Bank of China, at the end of 2020, the balance of inclusive small and micro loans was 15.1 trillion yuan, a year-on-year increase of 30.3%. Among them, the balance of farmers' production and operation loans was 5.99 trillion yuan, a year-on-year increase of 11.5%. In addition, as of the end of 2020, the balance of loans to registered poor people was 142.7 billion yuan. Considering the situation that they have escaped poverty but have not yet escaped the policy, the balance of loans to registered poor people and those who have been lifted out of poverty was 788.1 billion yuan. Digital inclusive finance aligns with this trend, providing farmers with access to sustainable finance, easing their financing constraints and meeting basic needs. This contributes to more resilient and sustainable opportunities for farmers to benefit from development in the digital era.

Simultaneously, China's agricultural sector has undergone significant strides in environmentally friendly and green development, aligning with broader societal shifts towards sustainability. Green agriculture, characterized by eco-friendly approaches and technological innovations, has gained momentum, enhancing production efficiency and product quality (Nourzad, 2002; Adnan et al., 2019; Liu Y. et al., 2021a).

While some existing theoretical studies have explored the possibility of digital financial inclusion in agricultural green development, such as through agricultural technology innovation and agricultural socialization services (Wang Lei, 2023), few scholars have measured the level of agricultural green development using a com-prehensive evaluation system and have cut through the pathway of digital financial inclusion as a driving force of agricultural green development from both macro and micro perspectives, and dig deep what kind of differences in spatial patterns this role has. In light of this gap, we attempt to explore the complex effects of digital financial inclusion driving agricultural green development in China based on a complete framework.

Specifically, the possible marginal contribution of this paper lies in three aspects. 1) Research Methodology. This paper draws on the "Measures for Monitoring and Evaluation of the Level of Agricultural Green Development (for Trial Implementation)" (2023) newly issued by the General Office of the Ministry of Agriculture and Rural Affairs of the People's Republic of China and existing literature to introduce agricultural scientific and technological development and agricultural output greening (Huang, 2021; Wang Lei, 2023). We develop a set of agricultural green development evaluation systems containing four first-level indicators and 18 second-level indicators, providing a more comprehensive measurement of agricultural green development, which is able to discuss its spatial and temporal evolutionary characteristics and its influence relation-ship with digital financial inclusion at a more subtle scale compared to the study by Jian (2023). 2) Research Perspective. Existing studies have only approached the subject from a single perspective of macro or micro (Jian, 2023; Wang Lei, 2023), while this paper explores the fundamental question of how digital financial inclusion mainly affects agricultural green development under the two perspectives of macro and micro. It comprehensively evaluates the effect of digital financial inclusion. 3) Research Content. This paper utilizes the spatial Durbin model to discover the spatial spillover effect of digital financial inclusion on agricultural green development. This

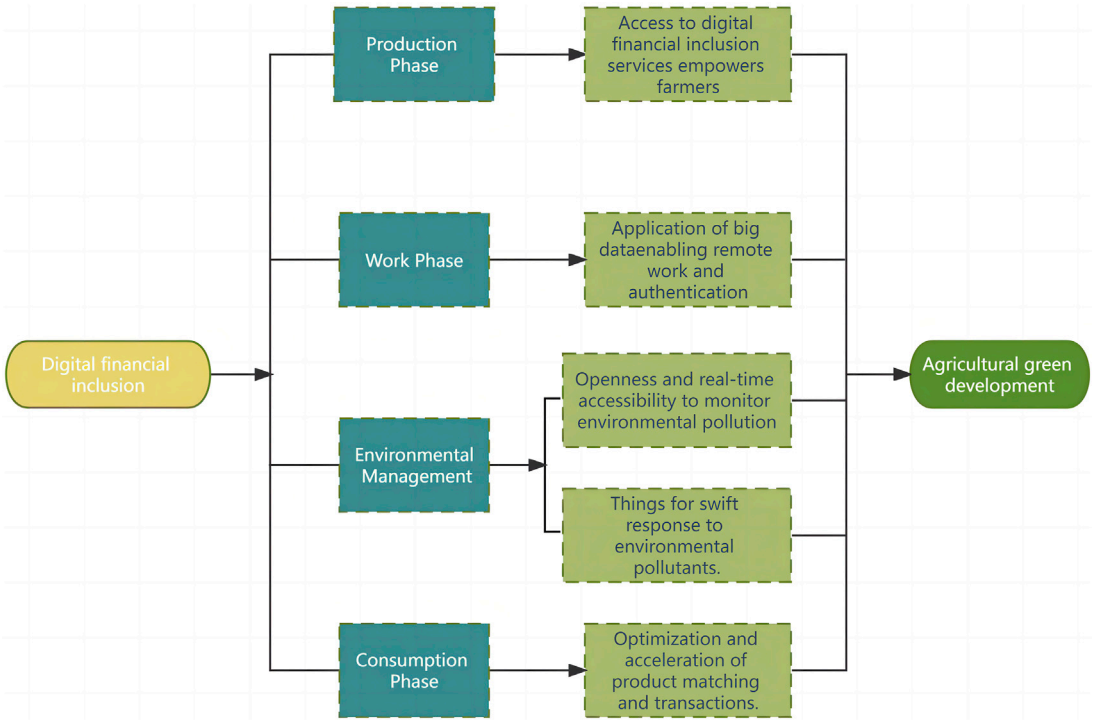


FIGURE 1
Direct mechanism path diagram.

broadens the scope of previous research and can more accurately measure the differential role characteristics of the two between regions.

2 Theoretical analysis and research hypothesis

2.1 Possible mechanisms of digital financial inclusion in influencing agricultural green development

2.1.1 Direct effect

China's information field continually witnesses the emergence of new technologies and forms (Han et al., 2024). Leveraging the Internet as a conduit, the integration and development of digital financial inclusion have interconnected financial services across the entire spectrum of production, distribution, exchange, and consumption (Guo et al., 2024). This integration furnishes innovative ideas for financially supporting agriculture and serves as a pivotal force in elevating the level of agricultural green development (Bondarenko et al., 2024).

Regarding production, farmers accessing digital financial inclusion services through online platforms conveniently and swiftly acquire information on the production, transportation, and sale of green agricultural products (Yu et al., 2020). This facilitates timely comprehension of the substantial market demand for green and healthy food, inherently motivating farmers to engage in green agricultural production (Panday et al., 2024).

In terms of work, digital financial inclusion employs big data to assess the credit status of farmers and small enterprises, thereby mitigating financing constraints resulting from information asymmetry or collateral shortages during the transition to environmentally friendly agricultural practices (Mhlanga, 2024). Moreover, it fosters the development of online businesses, enabling home-based work and remote authentication (Oanh, 2024). This reduces commuting, minimizes infrastructure, lowers energy consumption, and curtails auto-mobile emissions.

In the realm of environmental management, the advantages of digital financial inclusion, such as openness and real-time accessibility, address previous information asymmetry drawbacks (Hu et al., 2023). Leveraging technologies like big data, cloud computing, and the Internet of Things, environmental pollution in agricultural enterprises can be dynamically monitored and shared with governmental decision-makers, enterprises, and the public. This real-time monitoring enables swift responses to environmental pollutants, enhancing agricultural green development (Ataei Kachouei et al., 2023).

Concerning consumption, the evolution of digital financial inclusion optimizes and expedites product matching and transactions. The application of digital technology optimizes the cross-border allocation of limited resources (Pratama et al., 2023; Liu et al., 2024). The essence of digital financial inclusion, represented by the Internet, facilitates information exchange. The expanded scale and diversity of agricultural products generate a wealth of information, introducing complexity to the economic system and presenting new matching challenges. Emerging technologies like the Internet,

cloud computing, and big data offer avenues for optimizing economic market matching problems (Chen et al., 2014).

The framework diagram of the direct mechanism is shown in Figure 1.

2.1.2 Indirect effect

Digital financial inclusion plays a pivotal role in influencing agricultural green development by optimizing industrial structure upgrading and fostering entrepreneurial activity among farmers, which can be corresponded to "Structural" effects and "Active" effects.

From a macro perspective, digital financial inclusion has "Structural" effects. China's significant advancements in digital financial inclusion have triggered spurts in industrial structural evolution. Agricultural development's fundamental components have transitioned from land and labor to modern facets like science, technology, and human capital (Hong, 2023). Leveraging digital financial services such as the Internet and the Internet of Things, traditional industries realign factor resources, integrating and developing them with the information technology industry. This optimization process enhances production workflows, consistently augmenting production efficiency, and establishing an effective and environmentally friendly production mode. Through industrial association, integration, and innovation, traditional industries with high energy consumption, emissions, and pollution gradually phase out, fostering the upgrading of the industrial structure. Simultaneously, digital financial inclusion's financial support for rural industrial integration propels the comprehensive advancement of rural industries. Its digital attributes yield "digital dividends," amplifying the agricultural output's quality (Xu and Wang, 2023). This results in improved environmental quality, thereby augmenting economic growth and enhancing agricultural green development levels.

From a micro perspective, digital financial inclusion has "Active" effects. Digital financial inclusion significantly contributes to entrepreneurial activities (Xie et al., 2018). Its development offers a seamless information exchange platform, catering to the information needs of entrepreneurial farmers. Whether facilitating pre-entrepreneurial decision-making or aiding information exchange during entrepreneurial processes, it significantly promotes entrepreneurship (Zhou and Fan, 2018). On this basis, entrepreneurial activities in turn positively impact agricultural green development.

Specifically, for agri-entrepreneurial farmers, they often utilize entrepreneurial capital to expand agricultural production scales, initiate small agribusinesses, join agricultural cooperatives, etc. Grounded in the principles of the "rational economic man" and profit maximization, these entrepreneurial choices tend to favor activities with low energy consumption, minimal pollution, and government support, directly promoting agricultural green development (Li et al., 2020). For non-agricultural entrepreneurial farmers, digital financial inclusion empowers them with entrepreneurial capital. This prompts some farmers to diversify into non-agricultural entrepreneurship, reducing traditional agricultural production's frequency and associated pollution emissions. Additionally, it steers farmers towards industries closely linked to agriculture, reducing entrepreneurial risks while rationally adjusting industrial structures to minimize pollution and agricultural production risks. This strategic restructuring phase gradually replaces high-pollution, high-energy-consumption industries with low-pollution, energy-efficient green sectors, indirectly fostering agricultural green development.

In summation, digital financial inclusion emerges as a substantial driving force propelling agricultural green development in the contemporary era. Thus, we propose the following research hypotheses.

Hypothesis 1. "Byte-Sized Finance" (Digital financial inclusion) can directly contribute to "Bushel-Sized Benefits" (agricultural green development) on its own merits.

Hypothesis 2. "Byte-Sized Finance" generates "Bushel-Sized Benefits" by promoting the upgrading of industrial structure and enhancing the entrepreneurial activity of farmers. That is, with "Structural" effect and "Active" effect.

2.2 Spatial spillover effects of digital financial inclusion on agricultural green development

An essential aspect of digital financial inclusion lies in its ability to compress spatial and temporal distances through efficient information transfer, expanding interregional linkages in agricultural activities. Early attention to spatial spillovers resulting from informatization was observed in the empirical examination of a panel dataset comprising 48 states in the U.S.A. by Yilmaz et al. (2002). Keller (2002) furthered this perspective, exploring the spillover distance associated with knowledge and technology diffusion. In the Chinese context, studies by Su et al. (2021) and Fang et al. (2022) corroborate the idea that the Internet, particularly digital financial inclusion, exhibits spatial spillovers.

Moreover, agricultural activities demonstrate significant spatial relevance, with the Internet showcasing spatial spillover effects on regional agricultural development across various domains such as agricultural economic informatization (Xurui, 2022), agricultural mechanization (Sun et al., 2022), and agricultural green total factor productivity (Hu et al., 2022). Therefore, it follows logically that the influence of digital financial inclusion via the Internet on agricultural green development should similarly display spatial spillover effects. Consequently, we advance the following research hypothesis.

Hypothesis 3. "Byte-Sized Finance" (Digital financial inclusion) can act on agricultural green development in neighboring regions through spatial spillover effects, generating" Bushel-Sized Benefits".

3 Materials and methods

3.1 Model construction

Based on the above theoretical analysis, the following benchmark model is constructed to examine the direct impact of digital financial inclusion on agricultural green development:

$$\boldsymbol{Green_{it}} = \boldsymbol{\alpha_0} + \boldsymbol{\alpha_1 Dig_{it}} + \boldsymbol{\alpha_c X_{it}} + \boldsymbol{\mu_i} + \boldsymbol{\theta_t} + \boldsymbol{\varepsilon_{it}} \quad (1)$$

Here: $Green_{it}$ represents the level of agricultural green development of province i in period t, α_0 is a constant term.

Dig_{it} represents the level of digital financial inclusion in province i in period t, X_{it} is a series of control variables, containing level of financial support for agriculture (Fde), urbanization rate (Urb), human capital stock (Edu), *per capita* GDP (PGDP), and the agricultural disaster rate (Dis), are described in detail below. μ_i controls for province fixed effects. θ_t controls for time fixed effects. ε_{it} is random disturbance term.

Besides the direct impact Equation 1 captures, to explore potential indirect effects of digital financial inclusion on agricultural green development through alternative pathways, we conducted empirical analysis using mediation effect test methodology proposed by Zhonglin et al. (2004) and tested the results based on the Bootstrap method (with 1,000 resampled iterations) referring to Wu et al. (2021). This allowed us to examine the influence of digital financial inclusion on agricultural green development and its operational mechanisms within the context of our research inquiry. The specific model was structured as follows.

$$M_{it} = \beta_0 + \beta_1 Dig_{it} + \beta_c X_{it} + \mu_{1i} + \theta_{1t} + \varepsilon_{1it} \quad (2)$$

$$Green_{it} = \gamma_0 + \gamma_1 Dig_{it} + \gamma_2 M_{it} + \gamma_c X_{it} + \mu_{2i} + \theta_{2t} + \varepsilon_{2it} \quad (3)$$

Here: M_{it} represents intermediary variables, which will be described in detail below, and the other variables are explained as in Equation 1. Equation 2 shows the effect of digital financial inclusion on intermediary variables, and Equation 3 shows the joint effect of digital financial inclusion and intermediary variables on agricultural green development.

Finally, serving as a standard framework for spatial econometric modeling, spatial correlation arising from different sources is well captured by spatial Durbin models (Elhorst, 2014). Spatial correlation can originate from both the explained variables themselves, as well as from the explanatory variables and error terms. It can be adapted into common spatial lag and spatial error models by adjusting coefficient settings, thus enhancing its applicability (Beer and Riedl, 2012). Therefore, this paper considers introducing the spatial interaction term, for explanatory variable and control variables in Equation 1 respectively. This expansion transforms it into a spatial panel Durbin model, allowing for a more in-depth discussion of the spatial spillover effect of digital financial inclusion on agricultural green development.

Specifically, the natural logarithmic value (Log-L), likelihood ratio test (LR test), and Wald test are employed to determine whether the Spatial Durbin Model (SDM) needs to be downgraded. The Hausman test results reject the null hypothesis at the 1% significance level, indicating that the SDM with fixed effects is superior to the model with random effects. Collectively, these tests determined that the SDM model with spatiotemporal double fixed effects is the optimal choice.

$$Green_{it} = \delta_0 + \rho W Green_{it} + \varphi_1 W Dig_{it} + \delta_1 Dig_{it} + \varphi_2 W X_{it} + \delta_2 X_{it} + \mu_{3i} + \theta_{3t} + \varepsilon_{3it} \quad (4)$$

Here: ρ represents the spatial autoregressive coefficient, W is the spatial weight matrix. θ_{3t} controls for province fixed effects. In order to improve the robustness of the empirical results, this paper uses 2 spatial weight matrices, the first-order inverse distance weight matrix and the adjacency matrix, for the regression. φ_1 and φ_2 are the elasticity coefficients of the spatial interaction term for the core explanatory variables as well as the control variables.

3.2 Variable measurement and description

3.2.1 Agricultural green development (green)

While the significance of agricultural green production in agricultural green development is widely acknowledged in the academic realm, the prevailing evaluation index system predominantly emphasizes resource environment and agricultural production. However, due to measurement volatility and the limited dimensions, relying solely on these criteria fails to suffice for comprehensive research requirements in assessing agricultural green development. Consequently, an increasing number of scholars are resorting to multidimensional indicator systems to measure the level of agricultural green development.

Green agriculture aims at achieving four-fold integration and coordinated development involving agricultural economic growth, advancements in agricultural science and technology, ecological resource sustainability, and environmentally friendly agricultural output. Specifically, the system designed in this paper draws on Huang S (2021), Wang Lei (2023) and the most recent report by the General Office of China's Ministry of Agriculture and Rural Affairs on "Monitoring and Evaluation Measures for the Level of Agricultural Green Development (for Trial Implementation)" released in October 2023. It encompasses the attributes, objectives, pathways, and out-comes of agricultural green development.

To align more closely with the realistic context of synergistic governance of pollution and carbon emission reduction in China, we also include agricultural carbon emissions and agricultural non-point source pollution as some of the secondary indicators of the level of agricultural green development, thus obtaining the situations of clean and low-carbon transformation of agricultural production[1]. Consequently, we establish an Indicator System for agricultural green development, consisting of four primary and eighteen secondary indicators. These indicators are distributed across categories: greening of resources and the environment includes seven secondary indicators, agricultural economic development comprises four secondary indicators, agricultural science and technology development involves three secondary indicators, and greening of agricultural output encompasses four secondary indicators. Refer to Table 1 for a detailed breakdown.

To assess the level of agricultural green development in the 31 provinces (excluding Hong Kong, Macao, and Taiwan) from 2013 to 2021, we employed the entropy method, resulting in the Agricultural Green Development Index (AGDI). Figure 2 depicts the spatial distribution of agricultural green development levels in various provinces in 2013 and 2021.

3.2.2 Digital financial inclusion (dig)

Digital financial inclusion represents a modern financial model that amalgamates traditional business practices with digital

1 Thank the reviewers for the precious comments and suggestions.

TABLE 1 Evaluation index system of agricultural green development in Chinese provinces.

Dimensions	Indicators	Interpretations	Unit	Index type	Code
Greening of resources and environment	Pesticide use intensity	Average pesticide use per unit of agricultural land area	Tons/Ha	-	X_1
	Fertilizer use intensity	Average fertilizer use per unit of agricultural land area	Tons/Ha	-	X_2
	Utilization rate of agricultural plastic film	Agricultural film use/Cropland area	Tons/Ha	-	X_3
	Land re-cropping index	Ratio of total sown area of crops on cropland to cropland area	None	+	X_4
	Straw utilization rate	Comprehensive utilization of straw/Collectible resources of straw	%	+	X_5
	Comprehensive utilization rate of livestock and poultry waste	Amount of livestock manure utilized for integrated use/Total amount of livestock manure	%	+	X_6
	Forest cover	Forest area as a proportion of jurisdictional area	%	+	X_7
Agricultural economic development	Cultivated land area grain yield	Average annual food production per hectare of land	Kg/Ha	+	X_8
	Agricultural labor productivity	Average volume or value of agricultural products produced per unit of time per agricultural laborer	RMB/Year	+	X_9
	Agricultural industry structure index	Value added of primary sector as a share of regional GDP	None	+	X_{10}
	Agricultural productivity	Gross agricultural output/Total sown area of crops	Million/Hectare	+	X_{11}
Agricultural science and technology development	Growth rate of electricity consumption in agriculture	Growth rate of electricity use on rural sites in the current year compared to the previous year	None	+	X_{12}
	Growth rate of agricultural machinery power	Increase in the amount of mechanical power in agriculture in the current year over the previous year	Kilowatt	+	X_{13}
	Effective irrigation rate in agriculture	Effective irrigated agricultural area as a proportion of cultivated area	None	+	X_{14}
Greening of agricultural output	Agricultural carbon emissions	The sum of each carbon source multiplies its emission factor (see Supplementary Appendix SB for details)	10^4Tons	-	X_{15}
	Per capita rural solar water heaters	Rural solar water heaters/Rural population	10,000 Square Meters	+	X_{16}
	Growth rate of green food enterprise certification	Increase in the number of green food companies certified over last year's number	None	+	X_{17}
	Growth rate of green food labeled products	Increase in the number of green and organic landmark products over the previous year	None	+	X_{18}

technology, encompassing diverse sectors like insurance, securities, payments, and credit. In this study, we opt to gauge China's Digital Financial Inclusion Index (DFII), a collaborative effort between the Digital Finance Research Center of Peking University and Ant Financial Group (Guo et al., 2020). Widely adopted, this index serves as a benchmark for assessing the level of digital financial inclusion development across various regions in China. It comprises three dimensions: breadth of coverage, depth of use, and digitization, incorporating a total of 33 refined indicators. Figure 3 depicts the spatial distribution of the Digital financial inclusion levels in 2013 and 2021 by province.

Other variable definitions are in the Supplementary Appendix SA.

3.3 Data source

This study examines 279 balanced panel observations from 31 provinces in China (excluding Hong Kong, Macao, and Taiwan) spanning from 2013 to 2021. The data regarding the evaluation system for agricultural green financial development were sourced from the China Environmental Statistics Yearbook, China Rural Statistics Yearbook, China Statistics Yearbook, Green Food Statistics Yearbook, and the statistical yearbooks of provinces (municipalities) from previous years. Additionally, the data for the digital financial inclusion index were obtained from the Digital Financial Inclusion Index compiled by the Digital Finance Center of Peking University. Other variables were collected from various sources such as the China Statistical Yearbook, China Statistical Yearbook of Industrial Economy, China Agricultural Machinery Industry Year-book, and China Tertiary Industry Statistics Yearbook. Some of the missing data were processed using interpolation.

4 Results

The empirical test results are structured into four steps.

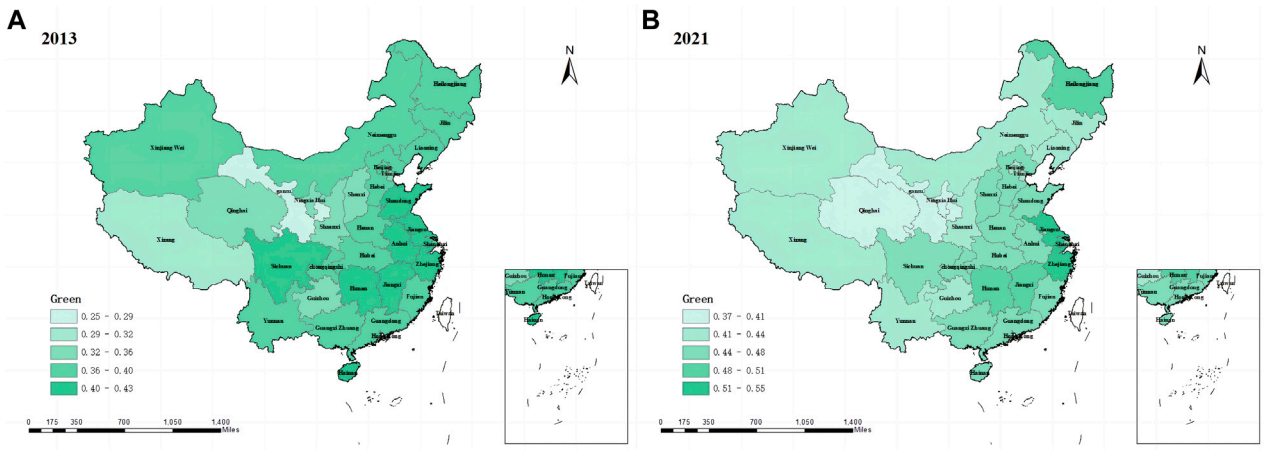


FIGURE 2
Agricultural green development level by provinces in 2013 and 2021, listed as: **(A)** 2013; **(B)** 2021.

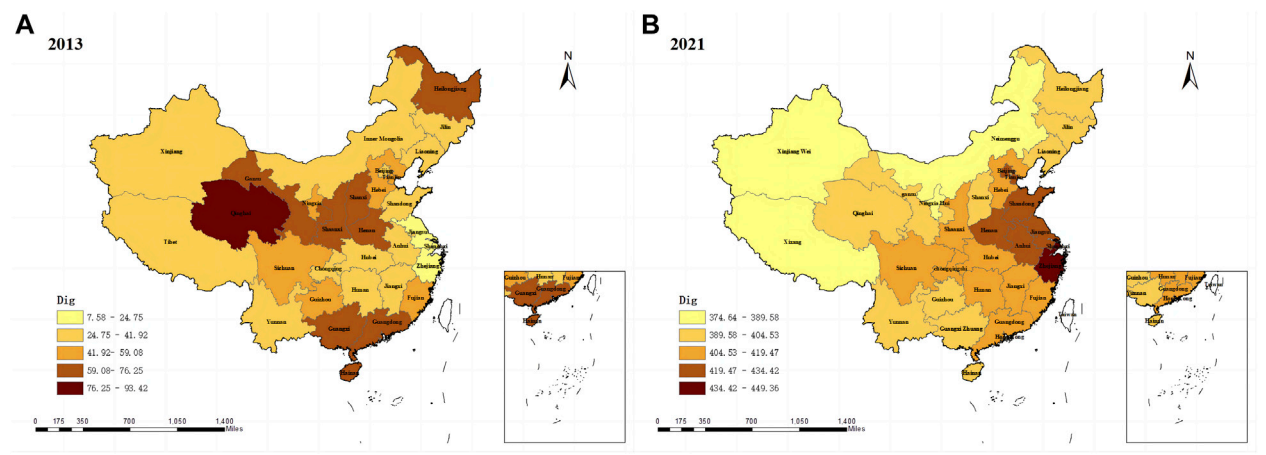


FIGURE 3
Digital financial inclusion level by provinces in 2013 and 2021, listed as: **(A)** 2013; **(B)** 2021.

Step 1. Examine whether digital financial inclusion directly impacts agricultural green development (Hypothesis 1).
Step 2. Test whether digital financial inclusion indirectly affects agricultural green development through the upgrading of industrial structure and the entrepreneurial activity of farmers. This step aims to analyze the "Structural" and "Active" effects of digital financial inclusion (Hypothesis 2).
Step 3. Explore the spatial spillover effect of digital financial inclusion on agricultural green development in neighboring provinces (Hypothesis 3).
Step 4. Test the robustness of results and analyze for any heterogeneity.

Descriptive statistics for the variables are presented in Table 2. To ensure accurate estimation results and minimize issues related to multicollinearity, we utilized the variance inflation factor method to assess the model (refer to Table 3). The results in Table 3 indicate

TABLE 2 Descriptive statistics of variables.

	Variables	N	Mean	sd	min	Max
Explained variable	Green	279	0.406	0.042	0.290	0.536
Explanatory variable	Dig	279	0.347	0.637	0.218	0.462
Control variables	Fde	279	0.117	0.035	0.041	0.204
	Urb	279	0.599	0.124	0.240	0.896
	Edu	279	1.259	0.202	0.753	1.774
	PGDP	279	1.110	0.567	0.224	3.824
	Dis	279	0.133	0.114	0.005	0.696
Intermediary variables	Ins	279	0.250	0.125	0.122	0.810
	Entrep	279	0.258	0.416	0.025	2.835

TABLE 3 Multiple collinearity test.

Variables	VIF	1/VIF
Dig	1.31	0.762025
Fde	3.08	0.324968
Urb	5.58	0.179160
Edu	2.05	0.487330
PGDP	1.82	0.550071
Dis	1.28	0.783269
Ins	5.09	0.196496
Entrep	3.11	0.321514

TABLE 4 Benchmark regression result.

Variables	Green	
	(1)	(2)
Dig	0. 206*** (3.68)	0.214*** (3.27)
PGDP		0.007 (0.91)
Fde		−0.189** (−1.98)
Edu		0.010 (0.39)
Dis		−0.008 (−0.67)
Urb		0.162** (1.87)
Constant term	0.338*** (24.75)	0.296*** (4.99)
Fixed provinces	YES	YES
Fixed time	YES	YES
Periods	9	9
Number of provinces	31	31
R^2	0.521	0.638

*t statistics in parentheses; *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

that the variance inflation factor of each variable is below 10, alleviating concerns regarding multicollinearity. Additionally, based on the Hausman test and F-test, the double fixed effects model was selected for further analysis.

4.1 Benchmark regression result

Table 4 presents the linear estimation outcomes illustrating the influence of digital financial inclusion on agricultural green development. The estimated coefficients of the key explanatory variable, the digital financial inclusion index (Dig), exhibit significantly positive values in both Model (1) and Model (2). These findings affirm that digital financial inclusion fosters favorable conditions for green agricultural development, even when considering the control variables. That is, "Byte-Sized Finance" does produce "Bushel-Sized Benefits." Consequently, it supports the validation of Hypothesis 1.

4.2 Test of possible mechanisms

The previous section presented a theoretical analysis of the transmission mechanism through which digital financial inclusion impacts green agricultural development, focusing on industrial structure upgrading at the macro level and the farmers' entrepreneurial motivation at the micro level. To empirically validate the existence of these transmission paths, this study utilizes the mediation effect model based on Equations 1–3, with regression results presented in Tables 5, 6.

From a macro perspective: Model (1) in Table 5 confirms the positive impact of digital financial inclusion on agricultural green development, while Model (2) verifies whether digital financial inclusion optimizes industrial structure upgrading. In both models, the regression coefficients of digital financial inclusion are positive and significant at the 1% level. Model (3) demonstrates that the influence of industrial structure (intermediary variable M) on the agricultural green development level is significantly positive. However, the estimated coefficient of digital financial inclusion is smaller than the 0.214 estimated in the benchmark regression model [Model (1)] and passes the 5% significance test. This suggests that industrial structure functions as an intermediary. The Sobel test confirms the hypothesis of a mediation effect. The intermediary effect size of industrial structure upgrading accounts for 24.40% of the total effect. This suggests that, from a macro perspective, digital financial inclusion optimizes the structure of the industry and thus contributes to agricultural green development. It has "Structural" effect.

From a micro perspective: Model (2) in Table 6 indicates a significantly positive impact of digital financial inclusion on the entrepreneurial activity of agricultural households at the 1% level. Subsequently, by reintroducing the intermediary variables of entrepreneurial activity into the regression equation for the impact of digital financial inclusion on agricultural green development, Model (3) shows a decreased and non-significant coefficient for the impact of digital financial inclusion compared to Model (1). This suggests that entrepreneurial activity also mediates the enhancement of digital financial inclusion in promoting agricultural green development. The Sobel test reveals the mediating effect of the entrepreneurial activity of farmers accounts for 14.60% of the total effect. This signifies that digital financial inclusion can boost agricultural green development by increasing farmers' entrepreneurial activity, thus significantly exhibiting the "active" effect of digital financial inclusion. This suggests that, at the micro level, digital inclusive finance can contribute to the agricultural green development by increasing farmers' entrepreneurial motivation. It has "Active" effect.

On this basis, we further tested the findings of the mediating effects of the two paths using the Bootstrap method (with 1,000 resampled iterations). The test results confirm that 'Byte-Sized Finance' generates "Bushel-Sized Benefits" by promoting the upgrading of the industrial structure and enhancing the entrepreneurial activity of farmers, through the "Structural" effect and the "Active" effect. Consequently, this supports the validation of Hypothesis 2.

TABLE 5 Validation of the transmission path of industrial structure upgrading.

Variables	Green	Ins	Green
	(1)	(2)	(3)
Dig	0.214*** (3.27)	0.516*** (6.80)	0.156** (2.19)
Ins			0.113** (2.02)
Control variables	YES	YES	YES
Fixed provinces	YES	YES	YES
Fixed time	YES	YES	YES
Periods	9	9	9
Number of provinces	31	31	31
R^2	0.638	0.793	0.645
Sobel test (Z-val)	2.861***		
Proportion of total effect that is mediated	24.4%		
Ind_eff test (P-val)	0.000***		
95% conf. interval	[0.047,0.193]		

*t statistics in parentheses; *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

TABLE 6 Validation of the transmission path of entrepreneurship of farmers.

Variables	Green	Entrep	Green
	(1)	(2)	(3)
Dig	0.214*** (3.27)	0.841*** (5.11)	0.006 (0.31)
Entrep			0.052*** (5.60)
Control variables	YES	YES	YES
Fixed provinces	YES	YES	YES
Fixed time	YES	YES	YES
Periods	9	9	9
Number of provinces	31	31	31
R^2	0.638	0.251	0.681
Sobel test (Z-val)	2.197***		
Proportion of total effect that is mediated	14.6%		
Ind_eff test (P-val)	0.002***		
95% conf. interval	[0.045, 0.230]		

*t statistics in parentheses; *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

4.3 Spatial spillover analysis

Before conducting spatial econometric analysis, it is crucial to examine the existence of a spatial effect on the variables under study, specifically the spatial autocorrelation of the digital financial inclusion development index and the agricultural green development index. In this paper, Moran's I index method is employed to compute the spatial effect for each year using the first-order inverse distance weight matrix, as presented in Table 7.

The results in Table 7 demonstrate that for the years 2013–2021, most Moran's I indices associated with the digital financial inclusion development index and agricultural green development index under the first-order inverse distance weight reach the 1% significance level. This signifies significant spatial autocorrelation in digital financial inclusion and agricultural green development across China's provinces from 2013 to 2021. These findings suggest a clustering phenomenon in the spatial distribution of both indices.

Based on Equation 4, Table 8 presents the outcomes derived from spatial regression models analyzing the impact of digital

TABLE 7 Validation of the transmission path of entrepreneurship of farmers.

Year	Dig		Green	
	Moran's I	Z-value	Moran's I	Z-value
2013	−0.001	1.018	0.427***	4.009
2014	−0.045	−0.371	0.516***	4.764
2015	0.075***	3.344	0.484***	4.503
2016	−0.010	0.755	0.447***	4.165
2017	0.027*	1.862	0.459***	4.181
2018	0.118***	4.713	0.398***	3.685
2019	0.112***	4.534	0.626***	5.600
2020	0.124***	4.873	0.469***	4.254
2021	0.143***	5.430	0.536***	4.904

*t statistics in parentheses; *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

financial inclusion on agricultural green development using two distinct spatial weight matrices. To gauge the robustness of the estimations of SDM model, this paper also showcases the estimation results of the spatial lag model (SAR) incorporating spatiotemporal double fixed effects. The findings in Table 8 reveal notable time lag effects and spatial spillover im-pacts on agricultural green development. Models (2) and (4) indicate significantly positive spatial autoregressive coefficients for agricultural green development, alongside significantly positive estimated coefficients for the spatial lag term of digital financial inclusion. These results imply that the level of digital financial inclusion in neighboring provinces exerts a positive effect on local agricultural green development.

This effect may be attributed to interregional economic competition and mutual emulation, where the digital financial inclusion and agricultural green development models in neighboring provinces demonstrate a robust effect on the local area. Moreover, the growing integration between regions fosters closer links in digital financial inclusion, facilitating the formation of both backward-forward and upstream-downstream linkages among industries with high correlations. Such connections support technology spillovers and knowledge dissemination, contributing to the favorability of neighboring regions' digital financial inclusion to local agricultural green development.

However, it's important to note that the values of spatial autoregressive coefficients cannot directly determine the marginal impact of digital financial inclusion on agricultural green development. Simple point regression results may lead to misestimation while assessing spatial spillover effects between regions. Hence, a comprehensive analysis using partial differential interpretation to explain variable changes, including direct and indirect effects, is necessary to ascertain the impact of the independent variable in one region on the dependent variable in both the same region and other regions.

Upon examining Table 8, the results indicate a significant indirect effect of digital financial inclusion on agricultural green development. "Byte-Sized Finance" can act on agricultural green development in neighboring regions through spatial spillover effects, generating" Bushel-Sized Benefits". Consequently, it supports the validation of Hypothesis 3.

TABLE 8 Results of the spatial model of digital financial inclusion affecting agricultural green development.

Model	SAR		SDM	
Spatial matrix types	Geographic distance matrix	Adjacency matrix	Geographic distance matrix	Adjacency matrix
Variables	(1)	(2)	(3)	(4)
ρ	0.674*** (9.57)	0.249*** (2.93)	0.490*** (4.78)	0.208** (2.41)
Dig	0.220*** (3.65)	0.182*** (3.04)	0.164*** (2.72)	0.130** (2.07)
W×Dig			1.483*** (4.04)	0.161** (2.43)
Control variables	YES	YES	YES	YES
Direct effect	0.238*** (3.59)	0.187*** (3.01)	0.149** (2.37)	0.142** (2.22)
Indirect effect	0.025 (0.71)	0.058* (2.31)	0.113** (2.97)	0.220*** (2.72)
Total effect	0.263* (2.59)	0.245*** (2.90)	0.262*** (3.42)	0.362*** (3.66)
Log-L	781.440	785.690	791.856	795.753
Fixed provinces	YES	YES	YES	YES
Fixed time	YES	YES	YES	YES
Wald test (P-value)	-	-	79.22 (0.000)	115.50 (0.000)
R^2	0.237	0.281	0.290	0.298

*t statistics in parentheses; *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

TABLE 9 Robustness test results.

Variables	Replacing core explanatory variables			Adding policy variable	System GMM model
	Breadth of coverage	Depth of use	Digitization		
	(1)	(2)	(3)	(4)	(5)
L1.Green				0.795*** (11.54)	
Dig				0.217*** (3.32)	0.323* (1.64)
Treat*Post				0.104** (2.12)	
Breadth of coverage	0.929*** (4.30)				
Depth of use		0.323*** (3.46)			
Digitization			0.226** (2.02)		
Control variables	YES	YES	YES	YES	YES
Fixed provinces	YES	YES	YES	YES	YES
Fixed time	YES	YES	YES	YES	YES
N	279	279	279	279	248
AR (2)	-	-	-	-	0.192
Sargan	-	-	-	-	0.393

t statistics in parentheses; *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

4.4 Robustness test

To determine the reliability of digital financial inclusion in bolstering agricultural green development, the article conducts rigorous tests, and the outcomes are presented in Table 9. Initially, the core explanatory variables are replaced. In models (1), (2), and (3), the measures of breadth of coverage, depth of use, and digitization all exhibit significant positive impacts at the 1% level. This indicates that altering the measures of the core explanatory variables doesn't significantly alter the estimation results, and the promotion effects, in descending order, are observed as breadth of coverage, depth of use, and digitization. Overall, the estimation results regarding the impact of different dimensions of digital financial inclusion on agricultural green development are largely consistent with the earlier findings regarding the influence of digital financial inclusion on green agricultural development.

Subsequently, highly correlated policy variable is added as another control variable, and enter the model in the form of dummy variables. The General Office of the CPC Central Committee and the General Office of the State Council issued the Opinions on the Establishment of Unified and Standardized National Ecological Civilization Pilot Zones on 22 August 2016. Taking into account the existing ecological civilization reform practice foundation, regional variability and development stage of each region, the first batch of Fujian, Jiangxi and Guizhou provinces, which have a better ecological foundation and stronger carrying capacity of resources and environment, were selected as the pilot zones. In model (4), the estimated coefficients and signs of digital financial inclusion exhibit no significant changes after incorporating the policy, confirming the robustness of the conclusions.

Thirdly, alternative models (system GMM) were used to further enhance the robustness of the article's conclusions. To verify the validity of the Gaussian mixed model estimation results, this study employs two tests, including the second-order serial autocorrelation test and the over-identification constraint test, to validate the model estimation results and the validity of instrumental variables. As shown in model (5), the Arellano-Bond test for AR (2) in first differences is 0.192 (greater than 0.05), which verifies the hypothesis that there is no second-order serial autocorrelation in the model. Additionally, the value of the Sargan test is greater than 0.05, which confirms that there is no over-identification of the instrumental variables, indicating that the model setting is reasonable and effective. The estimation results in model (5) also demonstrate a positive effect of digital financial inclusion on agricultural green development. These outcomes collectively affirm that digital financial inclusion indeed exerts a noteworthy promotional effect on agricultural green development.

4.5 Endogenous discussion

The main method to address the endogeneity problem caused by omitted variables and reverse causation is the selection of appropriate instrumental variables for the core explanatory variables. Following the methodology of Huang et al. (2019), the historical data of post and telecommunications of each province in 1984 is utilized as an instrumental variable for the digital financial inclusion development index. This selection is based on the premise that the vehicle for the development of digital financial inclusion is the information network, of which the Internet is a representative, and Internet access technology began with telephone dial-up access (PSTN), followed closely by fiber-optic broadband access technology. Such that places with historically high ownership of telephones are also likely to have high Internet penetration. Moreover, traditional telecommunication tools such as landline

TABLE 10 Instrumental variables regression.

Variables	Phase I: Dig		Phase II: Green	
IV	0.000*** (4.96)	0.000*** (3.49)		
Dig			0.097*** (4.21)	0.126*** (3.37)
Control variables	NO	YES	NO	YES
Fixed provinces	YES	YES	YES	YES
Fixed time	YES	YES	YES	YES
Kleibergen-Paap rk LM statistic	14.059 [0.000][1]	17.896 [0.000][1]		
Kleibergen-Paap rk Wald F statistic	20.923 {16.38}[2]	21.516 {16.38}[2]		
Periods	9	9	9	9
Number of provinces	31	31	31	31
R^2	0.779	0.748	0.970	0.989

1 [ ] value is P-value.
2 { } value is the Stock-Yogo weak discrimination test threshold at the 10% level.
*t statistics in parentheses; *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

telephones are unlikely to exert an impact on present-day agricultural green development, which meets the requirement of exclusivity. Therefore, using the number of telephones owned by provinces (excluding Chongqing) in 1984 as an instrumental variable satisfies the criteria of exogeneity and relevance. The data on telephone ownership by provinces in 1984 is derived from the Compendium of Fifty Years of Statistical Resources of New China.

However, as the instrumental variable comprises cross-sectional data, it cannot be directly employed in the econometric analysis of panel data. To address this issue, we introduce time series data and create an interaction term with the cross-sectional data to construct the panel instrumental variable, following Nunn and Qian (2014)'s approach. Specifically, the number of Internet users in the country in the previous year (time-series data) is separately constructed from the number of telephone sets owned in each province in 1984 (cross-sectional data) as an instrumental variable (IV) for the provincial digital financial inclusion index in that year. Subsequently, a two-stage least squares (2SLS) regression is conducted.

The outcomes depicted in Table 10 demonstrate that even after considering endogeneity, the effect of digital financial inclusion on enhancing agricultural green development remains significant at the 1% level. Additionally, regarding the original hypothesis of "insufficient identification of instrumental variables," the p-value of the LM statistic of Kleibergen-Paap rk is significant, rejecting the original hypothesis. Furthermore, in the test of weak identification of instrumental variables, the Wald F statistic of Kleibergen-Paap rk is greater than that of the Stock-Yogo weak identification test, signifying significance at the 10% level. The critical value of the Stock-Yogo weak identification test at the 10% level is 16.38. Overall, these tests validate the selection of the cross term between the historical number of telephones in each province and the number of Internet users in the country in the previous year as an instrumental variable for historical postal and telecommunications data.

4.6 Heterogeneity analysis

Regional heterogeneity in the distribution of agricultural green development exists due to varying resource endowments and developmental stages. This is typically observed when dividing up food-producing areas. In order to guarantee food security, China has established 13 main grain-producing regions: Liaoning, Hebei, Shandong, Jilin, Inner Mongolia, Jiangxi, Hunan, Sichuan, Henan, Hubei, Jiangsu, Anhui, and Heilongjiang. An overall sample regression might obscure regional characteristics. Therefore, before testing for categorical regression, the descriptive statistics of the differences in the levels of agricultural green development and digital financial inclusion between different regions are explained.

From Table 11, it can be seen that the major-grain-producing region is significantly ahead of the not-major-grain-producing in agricultural green development, reflecting the "first-mover advantage" of resource endowment. This result sets the foundation for testing the regional heterogeneity in the impact of digital financial inclusion on the level of green development in agriculture. Consequently, the sample is divided into major-grain-producing regions and not-major-grain-producing regions for regression in the heterogeneity analysis. The estimation results are presented in Table 12.

The results in models (1) and (2) show that the effect of digital financial inclusion on the promotion of not-major-grain-producing regions is significant at the 1% statistical level, while its positive effect on agricultural green development in major-grain-producing regions is not significant. The possible reasons for this are that the major-grain-producing areas are the primary source of food supply in China, and the frequent agricultural production activities, high intensity of agricultural inputs such as chemical fertilizers and pesticides, and serious pollution problems present greater obstacles to the promotion of agricultural green development by digital inclusive finance. This heterogeneous result also suggests that the role of digital inclusive finance in mitigating pollution and fostering green agriculture should be tailored to the specific conditions of

TABLE 11 Differences of digital financial inclusion and agriculture green development across regions.

Digital financial inclusion (Dig)					
Region	N	Mean	sd	min	Max
Major	108	0.349	0.063	0.224	0.431
Not-major	171	0.347	0.064	0.217	0.462
Agricultural Green Development (Green)					
Major	108	0.426	0.034	0.363	0.536
Not-major	171	0.393	0.042	0.289	0.525

major-grain-producing region. Furthermore, agricultural green transformation policies should be strategically focused on these primary food-producing areas to fully exploit the potential of digital inclusive finance in advancing the comprehensive and sustainable development of agriculture in these key regions.

5 Discussion

This paper has a high correlation with the existing research. For example, some theoretical studies delve into the role of digital financial inclusion in affecting green total factor productivity (Liu et al., 2023; Shen et al., 2023), agroecological efficiency (Ma and Li, 2021), farm income (Li et al., 2022), farmers' adoption of green production technologies (Carter et al., 2016; Zhou et al., 2022), carbon emission reduction (Wang et al., 2022a; Lee et al., 2022), and the convergence theme of green finance contributing to sustainable agricultural development (Mo et al., 2023). Some other theoretical studies have underscored the multidimensional impact of digital financial inclusion on agricultural green development, such as agricultural technological innovation and agricultural socialization services (Wang Lei, 2023).

However, significant gaps remain. What are the characteristics of this effect, and how can we capitalize on these effects for coordinated regional development? While these studies have provided valuable insights, they have often focused on either macro or micro perspectives, overlooking the holistic impact of digital financial inclusion across different levels.

Our study addresses this gap by providing a comprehensive analysis that integrates both macro and micro perspectives. At the micro-level, research suggests that digital financial inclusion fosters entrepreneurship among farmers (Liu Z. et al., 2021b; Ji et al., 2021). At the macro-level, studies propose that digital financial inclusion facilitates the upgrading of industrial structures (Ren et al., 2023; Zhang et al., 2023). By confirming these pathways of digital inclusive finance and further affirming its role in agricultural green development through these pathways, our findings address the question of how "Byte-Sized Finance" can yield "Bushel-Sized Benefits" in China's agricultural green development. It offers fresh evidence for the discussion of the "Structural" and "Active" impacts of digital inclusive finance on agricultural green development.

Furthermore, both digital financial inclusion and agricultural green development demonstrate the potential for spatial spillovers (Keller, 2002; Yilmaz et al., 2002; Su et al., 2021; Hu et al., 2022; Xurui, 2022). We confirm this through empirical analysis and provide policy suggestions on leveraging these effects to promote coordinated regional development in the agricultural sector, adding practical significance to our study.

This study still has some limitations. It is hoped that future research will further our study from the following aspects:

(1) Scale of Analysis. This study uses Chinese provincial-level regions as case areas due to data availability. Future research can conduct empirical studies at more granular levels to test whether the findings are equally applicable in smaller administrative units within China, such as the city or county level.
(2) Focus on Digital Finance. This study concentrates on the impact of digital financial inclusion on agricultural green development. Future research could expand this focus to assess the broader financial dividends from the integration of economy and technology on agricultural sustainability. Investigating the potential impacts of digital financial inclusion on other environmentally related areas of sustainable development would also be valuable.
(3) Geographical Applicability. This study focuses on the spatial spillover effects of digital financial inclusion within China. Further research should explore the applicability of these results to other developing countries and explore the potential spatial spillover effects of digital financial inclusion on agricultural green development.

TABLE 12 Heterogeneity analysis: grouping by food-producing regions.

Variables	Major-grain-producing area	Not-major-grain-producing areas
	(1)	(2)
Dig	0.118 (1.57)	0.460*** (3.33)
Control variables	YES	YES
Fixed provinces	YES	YES
Fixed time	YES	YES
N	108	171
R^2	0.742	0.509

*t statistics in parentheses; *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

6 Conclusion and policy implications

In this paper, "Byte-Sized Finance" refers to digital financial inclusion, which encompasses the use of digital technologies to provide financial services to individuals and businesses that are underserved by traditional financial institutions. The primary goal is to make financial services more accessible, affordable, and convenient, especially for rural and remote areas. " Bushel-Sized Benefits" refers to the significant benefits and improvements in agricultural green development and sustainability resulting from the application of digital financial services. Given the substantial impact of digital financial inclusion on agricultural green development in China, this study empirically examines the complex impacts of digital financial inclusion as driver of agricultural green development. The main conclusions are as follows:

(1) "Byte-Sized Finance" and "Bushel-Sized Benefits": Digital financial inclusion, referred to as "Byte-Sized Finance," can contribute to significant agricultural benefits, termed "Bushel-Sized Benefits." Digital financial inclusion significantly propels agricultural green development in China, emerging as a pivotal determinant in shaping agricultural sustainability in the contemporary era. The conclusions remain robust even after employing instrumental variables and conducting robustness tests, with digital financial inclusion demonstrates greater effectiveness in not-major-grain-producing areas.
(2) Mechanisms of Impact: "Byte-Sized Finance" generates "Bushel-Sized Benefits" through "Structural" effect and "Active" effect. It facilitates industrial structural upgrading and stimulates entrepreneurial activity among farmers, thus empowering agricultural green development.
(3) Spatial Spillover Effects: Digital financial inclusion can positively impact agricultural green development in neighboring regions through spatial spillover effects. Our empirical findings corroborate the presence of a spatial spillover effect of digital financial inclusion on provincial agricultural green development. This underscores the pivotal role of digital financial inclusion in fostering an interconnected and harmonized paradigm of green agriculture across regional boundaries. Such synergistic dynamics are instrumental in enhancing the standards, efficiency, and sustainability of Chinese agriculture.

Given the above conclusion, our study offers several policy implications. Firstly, boost investments in internet finance. Recognizing digital financial inclusion as a potent catalyst for agricultural sustainability necessitates a significant increase in investments in Internet finance. This can be achieved through the establishment of special demonstration zones that showcase the benefits of digital financial services in agriculture. Additionally, enhancing collaborative efforts among stakeholders—including government agencies, financial institutions, and tech companies—is essential. Conducting regular performance evaluations will further solidify the dividends gained from comprehensive financial service reforms. These steps are crucial in advancing agricultural green development by ensuring that digital financial inclusion reaches its full potential.

Secondly, implement tailored strategies for regional integration. While the positive impact of digital financial inclusion on agricultural green development is evident across China, deeper integration is required in the major-grain-producing areas. It is imperative to implement dynamic and tailored digital financial inclusion strategies that address the unique challenges and needs of these regions. Providing "hardware" technical support, such as improving digital infrastructure and offering targeted financial products, can effectively address regional disparities in resource endowments and heterogeneity in development characteristics. This approach ensures that all regions benefit equally from digital financial inclusion, thereby promoting balanced and sustainable agricultural growth.

Lastly, harness spatial spillover effects. Acknowledging the spatial spillover effects of digital financial inclusion activities implies the need to fully harness spatial contributions to agricultural green development. This can be achieved by enhancing coordination in constructing new infra-structure across different regions and aligning decision-making strategies from the CPC Central Committee and the State Council to foster inclusive finance. These approaches highlights the interconnectedness of regional agricultural systems and ensures that advancements in one area benefit neighboring regions as well.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

LZ: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. YQ: Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Visualization, Writing–original draft, Writing–review and editing. XD: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2024.1411866/full#supplementary-material

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Studying the risk spillover effects of the carbon market and high-carbon-emission industries under economic uncertainty

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In this paper, we select the China Carbon Market Price Index, which reflects the overall price changes in China's carbon market (CCM), and employs the TVP-VAR-BK model to examine the risk spillover effects between the carbon market and high-carbon-emission industries in China from a frequency domain viewpoint. Employing the nonparametric quantile Granger causality test, it delves further into the effects of economic policy uncertainty (EPU) in China on the degree of risk spillovers between the carbon market and high-carbon-emission industries. There are significant risk spillover effects between the carbon market and high-carbon-emission industries. During the short term, the carbon market affects the cement industry more than the electric power and steel industries. However, the carbon market is affected by the volatility of the high-carbon-emission industries over the long term. In addition, the effect of EPU on the magnitude of risk spillovers between the carbon market and high-carbon-emission industries is nonsignificant at extreme quartiles and significant at the middle quartile level, which is typically asymmetric.

KEYWORDS

carbon market, high-carbon-emission industries, ow-carbon economy, TVP-VAR-BK model, spillover effects, economic uncertainty

1 Introduction

As global warming has gotten worse over the past few years, the world's glaciers are melting rapidly (Tran, 2022), and the international community has come together to address this global crisis. The signing of the Kyoto Protocol and the Paris Agreement marked significant progress in strengthening cooperation on climate governance at the global level. In this context, the goals of "Carbon Peaking" and "Carbon Neutrality" demonstrate a firm stance on climate change in China (Zhang et al., 2023). A lot of attention has been paid by scholars to the carbon market as an important part of China's high-quality growth, green and low-carbon transformation, and reaction to global warming. The Chinese Listed Companies Carbon Emissions Ranking was released in Beijing on 17 November 2021. The list is divided into "total" and "intensity", which shows that electric power, steel, and cement are the top three carbon emission industries. Therefore, exploring the spillover effects between the carbon market and high-carbon-emission industries is vital for effectively controlling the risk of carbon trading, advancing the "double carbon" target and national conservation of energy and reduction of emissions.

As the CCM has steadily improved, some academics have started to concentrate on the ways that the spillover effects between the CCM and high-carbon-emission industries. Tang

et al. (2024) examined the risk spillover effects among China's electricity, coal and carbon markets using the DY spillover index. The empirical results show that there are significant long-term bidirectional asymmetric spillovers between these markets. In addition, extreme risk events significantly exacerbate the volatility spillover effects in the power, coal and CCM. Xu and Huang (2023) investigated the relations between the CCM and ten high-energy-consuming industries, such as electric power, paper, steel, and nonferrous metals, using the variance spillover index constructed with the TVP-VAR model. The research findings indicate that the CCM had a more profound effect on energy-intensive companies during the COVID-19 pandemic and the carbon market establishment, as well as a more closer risk contagion network. However, when most scholars study the spillover effect between CCM and high-carbon-emission industries, the selected CCM variables do not reflect the overall changes in CCM price as a whole. For example, Tao (2015) considered the completeness and authenticity of the data and thus studied the Shanghai carbon trading market. On the other hand, Wang and Wang (2022) studied the Hubei carbon trading market. Meanwhile, the existing literature has not overcome the shortcomings of the chosen model when exploring the relationship between carbon and financial markets from the frequency domain perspective. For example, Adekoya et al. (2021) used the BK model in order to investigate the spillover effects that occurred between the EU carbon market and a number of other commodities and financial markets at varying frequencies. Ding et al. (2022) utilized the DY and BK models to explore the time-frequency spillovers between the carbon market, the fossil energy market, and the clean energy market in both time and frequency domains. However, none of these modeling approaches can avoid the specific drawbacks of the rolling window VAR approach, such as the problems of arbitrarily choosing the size of the rolling window and the loss of observations.

In addition, another shortcoming of the existing studies is that they neglect to explore the impact of macroeconomic variables on the spillover effects between carbon markets and high-carbon-emission industries. Relevant studies have shown that economic policy uncertainty has significant explanatory power on financial market variables such as commodity prices (Prokopczuk et al., 2019), bond market volatility (Kim et al., 2024), foreign exchange spreads (Husted et al., 2018), and stock prices (Liang et al., 2020), and the impact is more significant, especially during the crisis. Therefore, it is important to explore the impact of EPU on the spillover effect between the carbon market and high-carbon-emission industries to realize the risk prevention and control between the carbon market and high-carbon-emission industries, as well as to introduce corresponding policies.

In summary, the main contributions of this paper are as follows: First, in order to better study the spillovers between the CCM and high-carbon-emission industries, this paper selects the Wind Power Industry Index, China Steel Price Index and China Cement Price Index as representative of high-carbon-emission industries and selects the China Carbon Trading Price Index constructed by Han and Jiang (2022) as representative of CCM, so that it can better reflect the spillover effect of overall price changes in the CCM on the high-carbon-emission industries. Second, this paper utilizes the BK spillover index constructed by the TVP-VAR model, which overcomes the shortcomings of the traditional BK spillover index model, in order to study the spillover effect between the carbon market and high-carbon-emission industries. Third, the impact of the EPU on the spillover effects between the CCM and high-carbon-emission industries is further explored. Overall, the research framework of this paper provides some new ideas for analyzing the spillover effects between carbon markets and high-carbon-emission industries, and the conclusions of this paper also have some guiding significance for the prevention of risk contagion in the process of carbon market construction.

The paper is structured as follows. The related literature review is in Section 2. The modeling methodology is in Section 3. The analysis of the empirical results, conclusions and policy recommendations are discussed in Sections 4, 5, respectively.

2 Literature review

The production of high-carbon-emission industries requires considerable energy consumption, such as natural gas, oil and coal. The use of these energy sources will exacerbate global warming, so most scholars pay more attention to the relationship between the carbon market and the energy needs of high-carbon-emission industries. Current research focus on the EU carbon market, the longest-established. Chen et al. (2022) used the QVAR model in order to investigate the connection between the carbon market and the energy and metal markets. Their analysis found a strong spillover impact between these two marketplaces, especially at the extreme quartile level. At the same time as Byun and Cho (2013) made the discovery that there is an asymmetric link between the volatility of carbon futures and energy volatility using the GARCH model, they also noticed the direction of the spillover. The findings of Byun and Cho (2013) were corroborated by Liu and Chen (2013), who conducted additional research to examine the extent of the spillover effects. Through the utilization of the TVP-VAR-SV model and impulse response function, Qiao et al. (2023) investigated the intensity of spillovers and the direction in which they occurred in the carbon, fossil energy, and electric power markets. In the end, the findings demonstrated that the carbon market, the fossil energy market, and the electricity market all exhibit time-varying asymmetric characteristics in terms of the intensity and direction of their spillovers. With the help of the quantile VAR network framework and the GARCHSK model, Zhou et al. (2022) discovered that there are considerable risk spillover effects between the carbon market, the energy market, and the nonferrous metal market., and these effects have significant dynamic characteristics. However, there are clear disparities in risk spillovers across dimensions. Numerous studies have been conducted on the carbon market and energy market in China, coinciding with the gradual establishment and improvement of the China carbon market (CCM). Sample entropy is used by Yin et al. (2021) to investigate the volatility link between the coal and CCM from a multiscale and crossover viewpoint. The study found some degree of synchrony between the two markets. In the current study, Song et al. (2022) examined the spillover effects between the CCM and energy market using the VAR model and the BEKK-MGARCH model. They found spillover effects between a part of the CCM and the energy market, but there is a difference in the direction and intensity of the spillover effect. Liu et al. (2023) employed the

TVP-Copula-CoVaR methodology to examine the spillover effect of extreme risk between the CCM and the energy market. Their results suggest that, in comparison to the energy market, the CCM is more vulnerable to severe external shocks.

Among the related volatility spillover studies, the literature mostly analyses the link between the carbon market and various financial markets from a time-domain perspective. Wang and Guo (2018) employed the spillover index developed by Diebold and Yilmaz (2012) to examine the presence of asymmetric spillover effects among the carbon, crude oil, and natural gas markets. Using a modified error variance decomposition and network analysis, Tan et al. (2020) analysed the linkages between the EU carbon market and other financial markets and found that the carbon market and the oil and equity and nonenergy commodity markets are closely linked. The "carbon-energy-finance" system is more heavily influenced by macroeconomic variables than commodities considerations. Zhang and Wei (2024) examined the volatility spillovers between energy, agriculture, metals and carbon markets using a TVP-VAR model and empirically showed that the overall volatility spillover intensity between these markets is relatively low compared to the total return spillover index, thus suggesting that the linkages between these markets are weaker during periods of market turbulence. At the same time, a number of researchers have also investigated the spillover impact between the carbon market and the financial market from the point of view of the frequency domain perspective. Wang and Wang (2022) employed the BK model to examine the spillover effect between the CCM and the electric power market. The findings revealed that the spillover level is most pronounced in the short term and least pronounced in the long term. Jiang and Chen (2022) investigated the spillover effects between metal, energy and carbon markets during the New Crown outbreak in both time and frequency domains using the DY spillover model and the BK spillover model, and the results showed that the total spillover effects between carbon markets and metal and energy were significantly higher in the post-epidemic period compared to the pre-epidemic period. Among the total spillovers, the short-term spillovers were significantly higher than the long-term spillovers.

In addition, as the financialization of the carbon market continues to advance, price volatility and potential risks are gradually interacting significantly with other financial markets (Xu, 2021). Many variables impact financial markets, including energy market volatility, military conflicts, monetary policies, economic policies, and unpredictabilities in financial and energy markets, can exacerbate carbon market volatility (Abbas et al., 2019; Yu et al., 2021; Ge et al., 2022; Zhang et al., 2022) and further diminish its effectiveness and impact in decreasing carbon emissions (Mamirkulova et al., 2020; Dou et al., 2022), while increased volatility in the carbon market leads to an increase in the volatility spillovers of the financial markets to which it is linked. Therefore, it is important to continue to investigate the influence of macroeconomic variables on the level of risk spillovers between carbon and other markets. Chevallier (2011) used three different datasets and two testing methods to find that the increasing uncertainty of annual compliance events explains the instability of carbon price fluctuations, indicating a connection between macroeconomics and carbon markets. Similarly, Koch (2014) argued that the correlation between carbon and financial markets can be significantly affected by uncertainty induced by macroeconomic shocks during financial crises.

A review of the literature shows that, first, the above studies on the selection of the CCM variables mostly selected one or more carbon markets as representative of the China carbon market, thus failing to reflect the total CCM price shift. Second, the majority of previous research focuses on time domain analysis between the carbon market and high-carbon-emission industries. Although some scholars have also conducted research in the frequency domain, the selected model has not overcome the rolling window VAR method's drawbacks. Finally, existing studies do not further explore the influence of macroeconomic variables on the spillover effects between the carbon market and other markets.

3 Materials and methods

3.1 TVP-VAR-DY

Since Sims (1980) proposed the VAR model, it has been widely used in economic research. However, due to the defects of the model, Sims (1986) improved it and proposed the structural vector autoregressive SVAR model. Primiceri (2005) improved the TVP-VAR model on the basis of the SVAR model, which well solves the problem of effective estimation of nonlinear time series in the SVAR model.

Antonakakis and Gabauer (2017) made a time-varying volatility spillover index using the TVP-VAR model and the method for making a spillover index by Diebold and Yilmaz (2012). This method is called the TVP-VAR-DY methodology in this paper. The TVP-VAR(p) equation is:

$$\boldsymbol{y_t} = \boldsymbol{\Phi_{1t}}\boldsymbol{y_{t-1}} + \boldsymbol{\Phi_{2t}}\boldsymbol{y_{t-2}} + ... + \boldsymbol{\Phi_{pt}}\boldsymbol{y_{t-p}} + \boldsymbol{\epsilon_t}(\boldsymbol{x}) \quad \boldsymbol{\epsilon_t} \sim \boldsymbol{N}(\boldsymbol{0}, \Sigma_t) \quad (1)$$

where y_t and ϵ_t are $N \times 1$ vectors, Σ_t is the $N \times N$ time-varying variance–covariance matrix, Φ_{it} are the $N \times N$ time-varying VAR coefficients, and $i = 1, ..., p$. Using the matrix lag-polynomial $\Phi(L) = [I_N - \Phi_{1t}L - ... - \Phi_{pt}L^p]$ and the Wold representation theorem, the smooth TVP-VAR process can be rewritten in the form of TVP-VMA(∞): $x_t = \Psi(L)\epsilon_t$, where $\Phi(L) = [\Psi(L)]^{-1}$. $\Psi(L)$ has infinite lag terms, thus it is approximated by Ψ_h, which is calculated on these lag orders of $h = 1, ...H$ (Chatziantoniou et al., 2021).

The generalised forecast error variance decomposition (GFEVD), which indicates the impact of a shock to variable j on the forecast error variance of variable i, can be calculated using the TVP-VMA coefficient $\boldsymbol{\Psi}h$. It is written as follows:

$$\boldsymbol{C_{ijt}}(\boldsymbol{H}) = \frac{(\boldsymbol{\Sigma_t})^{-1}\sum_{h=0}^{H}\left((\boldsymbol{\Psi_h}\boldsymbol{\Sigma_t})_{ijt}\right)^2}{\sum_{h=0}^{H}\left(\boldsymbol{\Psi_h}\boldsymbol{\Sigma_t}\boldsymbol{\Psi'_h}\right)_{ii}} \quad (2)$$

$$\tilde{\boldsymbol{C}}_{\boldsymbol{ijt}}(\boldsymbol{H}) = \frac{\boldsymbol{C_{ijt}}(\boldsymbol{H})}{\sum_{k=1}^{N}\boldsymbol{C_{ijt}}(\boldsymbol{H})} \quad (3)$$

where $\tilde{C}_{ijt}(H)$ denotes the contribution of variable j to the variance of the prediction error of variable i at level H. By row normalisation of $\tilde{C}_{ijt}(H)$, we can obtain $\sum_{i=1}^{N}\tilde{C}_{ijt}(H) = 1$ and $\sum_{j=1i=1}^{N}\tilde{C}_{ijt}(H) = N$.

With Equations 2, 3, all risk spillover levels can be calculated, including:

Total spillover index:

$$\mathbf{TACL}_t(\boldsymbol{H}) = \boldsymbol{N}^{-1}\sum_{i=1}^{N}\mathbf{TO}_{it}(\boldsymbol{H}) = \boldsymbol{N}^{-1}\sum_{i=1}^{N}\boldsymbol{FROM}_{it}(\boldsymbol{H}) \tag{4}$$

The bigger the total spillover index, the stronger the relationship between the variables in the system. This coefficient shows the contribution of mutual spillovers between variables to the total forecast error variance.

Net pairwise directional spillover:

$$\boldsymbol{NPDC}_{ijt}(\boldsymbol{H}) = \tilde{\boldsymbol{C}}_{ijt}(\boldsymbol{H}) - \tilde{\boldsymbol{C}}_{jit}(\boldsymbol{H}) \tag{5}$$

It is the difference between the shock from variable i to variable j and the shock from variable j to variable j, and it shows the net spillover between two variables in the system.

Total Spillover TO others:

$$\boldsymbol{TO}_{it}(\boldsymbol{H}) = \sum_{i=1,i=j}^{N}\tilde{\boldsymbol{C}}_{jit}(\boldsymbol{H}) \tag{6}$$

It represents the spillover effect of variable i on all the other variables in the system.

Total Spillover FROM others:

$$\boldsymbol{FROM}_{it}(\boldsymbol{H}) = \sum_{j=1,i\neq j}^{N}\tilde{\boldsymbol{C}}_{ijt}(\boldsymbol{H}) \tag{7}$$

It represents the spillover effect of all the other variables in the system to variable i.

Net spillover effects:

$$\boldsymbol{NET}_{it}(\boldsymbol{H}) = \boldsymbol{TO}_{it}(\boldsymbol{H}) - \boldsymbol{FROM}_{it}(\boldsymbol{H}) \tag{8}$$

It shows how variable i has a net spillover effect on all other variables. When $NET_{it}(H) > 0$, this indicates that the shock of variable i on all other variables is greater than the shock of the other variables on i.

3.2 TVP-VAR-BK

By integrating the TVP-VAR model with the BK model, which was presented by Baruník and Křehlík (2018), we can investigate the frequency domain volatility spillovers between variables. The frequency response function $\Psi(e^{-i\omega}) = \sum_{h=0}^{\infty} e^{-i\omega h}\Psi_h\ (i = \sqrt{-1})$, y_t can be written at frequency ω as:

$$\boldsymbol{S}_y(\boldsymbol{\omega}) = \sum_{h=-\infty}^{\infty}\boldsymbol{E}\left(\boldsymbol{y}_t\boldsymbol{y}_{t-h}^{'}\right)\ \boldsymbol{e}^{-i\omega h} = \boldsymbol{\Psi}\left(\boldsymbol{e}^{-i\omega h}\right)\Sigma_t\Psi'\left(\boldsymbol{e}^{+i\omega h}\right) \tag{9}$$

Normalised processing is applied to the frequency domain generalised forecast error variance decomposition, and its equation is:

$$\boldsymbol{C}_{ijt}(\boldsymbol{\omega}) = \frac{(\Sigma_t)_{jj}^{-1}\left|\sum_{h=0}^{\infty}\left(\Psi\left(\boldsymbol{e}^{-i\omega h}\right)\Sigma_t\right)_{ijt}\right|^2}{\sum_{h=0}^{\infty}\left(\Psi\left(\boldsymbol{e}^{-i\omega h}\right)\Sigma_t\Psi\left(\boldsymbol{e}^{i\omega h}\right)\right)_{ii}} \tag{10}$$

$$\grave{\boldsymbol{C}}_{ijt}(\boldsymbol{\omega}) = \frac{\boldsymbol{C}_{ijt}(\boldsymbol{\omega})}{\sum_{k=1}^{N}\boldsymbol{C}_{ijt}(\boldsymbol{\omega})} \tag{11}$$

Aggregating all the frequencies in a given range to calculate spillovers in the short and long term, rather than at a single frequency, yields $\grave{\theta}_{ijt}(d) = \int_a^b \grave{\theta}_{ijt}(\omega)d\omega$, where $d = (a,b)$: $a,b \in (-\pi,\pi), a<b$; furthermore, the magnitude of risk spillovers can be calculated at all frequencies.

$$\boldsymbol{NPDC}_{ijt}(\boldsymbol{d}) = \grave{\boldsymbol{C}}_{ijt}(\boldsymbol{d}) - \grave{\boldsymbol{C}}_{jit}(\boldsymbol{d}) \tag{12}$$

$$\boldsymbol{TO}_{it}(\boldsymbol{d}) = \sum_{i=1,i\neq j}^{N}\grave{\boldsymbol{C}}_{jit}(\boldsymbol{d}) \tag{13}$$

$$\boldsymbol{FROM}_{it}(\boldsymbol{d}) = \sum_{j=1,i\neq j}^{N}\grave{\boldsymbol{C}}_{ijt}(\boldsymbol{d}) \tag{14}$$

$$\boldsymbol{NET}_{it}(\boldsymbol{d}) = \boldsymbol{TO}_{it}(\boldsymbol{d}) - \boldsymbol{FROM}_{it}(\boldsymbol{d}) \tag{15}$$

$$\boldsymbol{TACI}_t(\boldsymbol{d}) = \boldsymbol{N}^{-1}\sum_{i=1}^{N}\boldsymbol{TO}_{it}(\boldsymbol{d}) = \boldsymbol{N}^{-1}\sum_{i=1}^{N}\boldsymbol{FROM}_{it}(\boldsymbol{d}) \tag{16}$$

Additionally, we have

$$\boldsymbol{CN}(\boldsymbol{H}) = \sum_{\boldsymbol{d}}\boldsymbol{CN}(\boldsymbol{d}) \tag{17}$$

Where $CN(\cdot) = [NPDC, TO, FROM, \mathrm{NET}, TACL]$ denote the frequency net pairwise directional spillover, frequency spillover effects to others, frequency spillover effects from others, frequency net spillover effects, and frequency total spillover effects, respectively.

3.3 Nonparametric quantile Granger causality test

To continue to examine the effects of EPU on spillovers between variables, this study employs the nonparametric quantile Granger causality test developed by Balcilar et al. (2016), building upon the research conducted by Nishiyama et al. (2011) and Jeong et al. (2012). This test is effective in determining causal relationships between variables.

In the model, if x_t denotes the explanatory variables and y_t denotes the explained variables, then

$$\boldsymbol{Q}_{\boldsymbol{\theta}}\left(\boldsymbol{y}_t \mid \boldsymbol{y}_{t-1},\cdots,\boldsymbol{y}_{t-p},\boldsymbol{x}_{t-1},\cdots,\boldsymbol{x}_{t-p}\right) = \boldsymbol{Q}_{\boldsymbol{\theta}}\left(\boldsymbol{y}_t \mid \boldsymbol{y}_{t-1},\cdots,\boldsymbol{y}_{t-p}\right) \tag{18}$$

$$\boldsymbol{Q}_{\boldsymbol{\theta}}\left(\boldsymbol{y}_t \mid \boldsymbol{y}_{t-1},\cdots,\boldsymbol{y}_{t-p},\boldsymbol{x}_{t-1},\cdots,\boldsymbol{x}_{t-p}\right) \neq \boldsymbol{Q}_{\boldsymbol{\theta}}\left(\boldsymbol{y}_t \mid \boldsymbol{y}_{t-1},\cdots,\boldsymbol{y}_{t-p}\right) \tag{19}$$

Equation 18 indicates that the variable x_t is not a nonlinear Granger cause of the y_t in the θ quantile at lag order P, and Equation 19 indicates that the variable x_t is a nonlinear Granger cause of variable y_t in the θ quantile at lag order P, where $Q_\theta(y_t \mid \cdot)$ denotes that variable y_t is in the θth quantile $(0 < \theta < 1)$.

Letting $Y_{t-1} \equiv (y_{t-1},\cdots,y_{t-p})$, $X_{t-1} \equiv (x_{t-1},\cdots,x_{t-p})$, $Z_t \equiv (X_t, Y_t)$, $F_{y_t|Z_{t-1}}(y_t \mid Z_{t-1})$ and $F_{y_t|Y_{t-1}}(y_t \mid Y_{t-1})$ are the conditional distributions of y_t under Z_{t-1} and Y_{t-1}, respectively.

And letting $Q_\theta(Z_{t-1}) \equiv Q_\theta(y_t \mid Z_{t-1})$ and $Q_\theta(Y_{t-1}) \equiv Q_\theta(y_t \mid Y_{t-1})$, it can be shown that the probability of occurrence of $F_{y_t|Z_{t-1}}\{Q_\theta(Z_{t-1} \mid Z_{t-1})\} = \theta$ is 1. Then, according to Equations 18, 19, the following hypothesis can be proposed:

$$\boldsymbol{H}_0\colon \boldsymbol{P}\left\{\boldsymbol{F}_{\boldsymbol{y}_t|\boldsymbol{Z}_{t-1}}\{\boldsymbol{Q}_{\boldsymbol{\theta}}(\boldsymbol{Y}_{t-1})|\boldsymbol{Z}_{t-1}\} = \boldsymbol{\theta}\right\} = \boldsymbol{1} \tag{20}$$

$$H_1\colon P\left\{F_{y_t|Z_{t-1}}\{Q_\theta(Y_{t-1}) \mid Z_{t-1}\} = \theta\right\} < 1 \tag{21}$$

Jeong et al. (2012) measure quantile causality using the distance measure $J = \{\varepsilon_t E(\varepsilon_t \mid Z_{t-1}) f_z(Z_{t-1})\}$, where ε_t is the regression error term and $f_Z(Z_{t-1})$ is the marginal density function of Z_{t-1} i. The original hypothesis H_0 holds if and only if $E[I\{y_t \le Q_\theta(Y_{t-1}) \mid Z_{t-1}\}] = \theta$ or $I\{y_t \le Q_\theta(Y_{t-1})\} = \theta + \varepsilon_t$, where $I\{\cdot\}$ is the indicator function. The formula for the distance measure is:

$$\hat{J}_T = \frac{1}{T(T-1)h^{2p}} \sum_{t=p+1}^{T} \sum_{s=p+1, s\neq t}^{T} K\left(\frac{Z_{t-1} - Z_{s-1}}{h}\right) \hat{\varepsilon}_t \hat{\varepsilon}_s \tag{22}$$

In Equation 22, $K(\cdot)$ is the kernel function, h is the bandwidth, T is the sample capacity, p is the lag order of the vector Z_t, $\hat{\varepsilon}_t$ is the estimation of the unknown regression error, and $\hat{\varepsilon}_t = I\{y_t \le Q_\theta(Y_{t-1})\} - \theta$, which is estimated by using nonparametric kernel methods for $Q_\theta(Y_{t-1})$:

$$\hat{Q}_\theta(Y_{t-1}) = \hat{F}^{-1}_{y_t|Y_{t-1}}(\theta \mid Y_{t-1}) \tag{23}$$

In Equation 23, $\hat{F}_{y_t|Y_{t-1}}(y_t \mid Y_{t-1})$ denotes the Nadarya–Watson kernel estimator with the following expression:

$$\hat{F}_{y_t|Y_{t-1}}(y_t \mid Y_{t-1}) = \frac{\sum_{s=p+1, s\neq t}^{T} L\left(\frac{Y_{t-1} - Y_{s-1}}{h}\right) I(y_s \le y_t)}{\sum_{s=p+1, s\neq t}^{T} L\left(\frac{Y_{t-1} - Y_{s-1}}{h}\right)} \tag{24}$$

The kernel function is represented by $L(\cdot)$ in Equation 24, while the bandwidth is represented by h. Balcilar et al. suggested a higher-order quantile causality testing model based on Nishiyama et al. and the research framework of Jeong et al.

$$y_t = g(Y_{t-l}) + \sigma(X_{t-l})\varepsilon_t \tag{25}$$

In Equation 25, ε_t is the white noise process, and $g(\cdot)$ and $\sigma(\cdot)$ are equal to the unknown functions that satisfy the smoothness condition. Equation 26 is reformulated as the null alternative hypothesis for variance causality as follows:

$$H_0\colon P\left\{F_{y_t^2|Z_{t-1}}\{Q_\theta(Y_{t-1}) \mid Z_{t-1}\} = \theta\right\} = 1 \tag{26}$$

$$H_1\colon P\left\{F_{y_t^2|Z_{t-1}}\{Q_\theta(Y_{t-1}) \mid Z_{t-1}\} = \theta\right\} < 1 \tag{27}$$

To obtain the feasible test statistic, the y_t in Equations 22–24 is replaced by y_t^2 and the sequential test method described by Nishiyama et al. is introduced. First, the nonparametric Granger causality is evaluated for the first-order moment (k = 1). The original hypothesis is rejected at k = 1 because there is no causal link between EPU and spillovers between carbon markets and high-carbon-emission industries. Next, a second-order moment (k = 2) causality test is performed in the study. The empirical findings demonstrate the existence of a strong causal link. The lag order p in the nonparametric quantile causality test model was established using the Schwarz information criterion, Gaussian-type kernels were eventually employed for $K(\cdot)$ and $L(\cdot)$, and the bandwidth h was chosen using least squares cross-validation procedures.

TABLE 1 Descriptive statistics for samples.

	CCM	CEI	CSI	CCI
Mean	57.99656	3,341.433	137.6177	129.6211
Stdndard Deviation	28.48482	632.0163	34.28051	32.22320
Skewness	0.914069	1.131949	−0.072215	−0.015922
Kurtosis	3.181405	4.595387	2.507697	2.209719
Jarque-Bera	14.06248	31.96037	1.096759	2.606491

Note: *, **, *** indicate significant at the 10%, 5%, and 1% levels, respectively.

4 Results

4.1 Data

4.1.1 Data selection

To investigate the influence of the CCM and high-carbon-emission industries, this paper selects the China Carbon Market Price Index constructed by Han and Jiang (2022) for the carbon market variables. The index is based on the average price of transactions in the seven carbon markets of Shenzhen, Shanghai, Beijing, Guangdong, Tianjin, Hubei and Chongqing, and is compiled accordingly using the Paasche Index methodology with monthly data. In the selection of variables for the electric power industry (CPI), steel industry (CSI) and cement industry (CCI), the Wind Power Industry Index, China Steel Price Index and China Cement Price Index are selected as representatives of the three industries. For the empirical analysis, we follow Yu et al. (2021) and use monthly data to measure the spillover effects between the CCM and high-carbon-emission industries in the short-term (1–3 months) and long-term (more than 3 months) scenarios. The starting point of the empirical evidence is August 2014, the starting date of the China carbon market price index was constructed by Han and Jiang (2022), and the sample study interval was from August 2014 to September 2022. The EPU index is selected from the China Economic Policy Uncertainty Index constructed by Baker et al. (2016). The Wind database is the source of the data.

4.1.2 Descriptive statistics

Table 1 shows the descriptive statistics of the CCM price index, the power industry index, the steel industry index, and the cement price index. Analyzed from the viewpoint of standard deviation, the data of each series have different volatility, with the most drastic fluctuation in the electric power industry, and a greater degree of volatility in the iron and steel industry, the cement industry, and the domestic carbon market. From the viewpoint of kurtosis coefficient and skewness coefficient, the skewness of each series is not 0, and the kurtosis is significantly larger than 2, showing significant sharp peaks and thick tails. The value of Jarque-bara statistic of the original series of CCM and electric power industry at 5% level is 14.062 and 31.960 respectively, which significantly rejects the original hypothesis, so it does not obey normal distribution. However, the values of Jarque-Bara statistic for steel industry and cement industry at 5% level are 1.097 and 2.606 respectively, which do not reject the original hypothesis and obey normal distribution.

TABLE 2 ADF test.

Test variables	Test classes (C,T,P)	ADF statistical values	1% Critical value	5% Critical value	10% Critical value	Conclusion
CCM	(0,T,0)	−3.205	−4.053	−3.456	−3.154	stationary
CPI	(0,T,0)	−2.715	−4.053	−3.456	−3.154	Nonstationary
CSI	(0,T,0)	−2.968	−4.053	−3.456	−3.154	Nonstationary
CCI	(C,0,0)	−1.224	−3.498	−2.891	−2.583	Nonstationary
EPU	(0,T,0)	−3.927	−4.053	−3.456	−3.154	stationary

Note: (C, T, P) represent the constant term, time trend term, and lag terms, respectively, where 0 indicates the absence of this term. The selection of lag terms depends on the SIC.

TABLE 3 Total spillover effects.

	CCM	CPI	CSI	CCI	From
CCM	50.91	23.07	23.66	2.36	49.09
CPI	21.64	31.83	32.37	14.17	68.17
CSI	21.70	31.55	32.69	14.05	67.31
CCI	19.21	19.76	21.78	39.25	60.75
TO	62.55	74.38	77.80	30.59	TCI
Net	13.46	6.20	10.49	−30.16	61.33

TABLE 4 Total spillover effects in the short term (1–3 months).

	CCM	CPI	CSI	CCI	From
CCM	39.58	19.77	20.61	1.47	41.85
CPI	20.57	27.86	28.83	9.92	59.33
CSI	20.59	27.50	29.01	9.70	57.79
CCI	18.29	18.06	20.07	33.60	56.43
TO	59.45	65.32	69.52	21.09	TCI
Net	17.61	6.00	11.73	−35.33	53.85

4.1.3 Data testing

A smoothness test needs to be performed on the raw data before empirical evidence is collected to prevent pseudoregression. The ADF test results in Table 2 show that the China carbon trading market price is stationary at the 10% significance level. The power industry index, steel industry index and cement price index cannot reject the original hypothesis at three significance levels, indicating that the original series are not stationary. The China Economic Policy Uncertainty Index is stationary at the 5% significance level. Therefore, this paper selects the original CCM price and the original China economic policy uncertainty index as well as the first-order difference series of the electric power industry, the steel industry index, and the cement price index for the subsequent empirical study.

4.2 Empirical results

4.2.1 Static spillover effect results

Table 3 presents the total spillover effects between the CCM and high-carbon-emission industries, while Tables 4, 5 demonstrate the short-term and the long-term results of the spillover effects. The total spillover effects have an average value of 61.33%, which is divided into 53.85% attributable to short-term spillover effects and 7.48% attributable to long-term spillover effects. This indicates that 61.33% of the total spillover effects in the network "CCM – high-carbon-emission industries" come from the network itself and that the CCM has considerable spillover effects on high-carbon-emission industries. According to frequency domain decomposition, short-term spillovers dominate the CCM and high-carbon-emission industries spillovers. In terms of net spillover effects to others, it may be seen quite plainly that the CCM has the largest net spillover effect of 13.46%, which is the main exporter of spillover effects in the network "CCM – high-emission-carbon industries", followed by the steel industry and the electric power industry. Therefore, in the network "CCM – high-carbon-emission industries", the CCM will have a substantial influence on high-carbon-emission industries. Regarding the net spillover effects from others, the main net recipient in the network "CCM and high-carbon-emission industries" is the cement industry, with a value of −30.16%. From the frequency domain decomposition standpoint, the cement industry has the greatest impact in the short term, at −35.33%, while in the long term, it is a net exporter with a net spillover effect of 5.17%.

4.2.2 Dynamic spillover effect results

4.2.2.1 Total spillover effects of the "carbon markets – high-carbon-emission industries" network

The frequency domain decomposition in Figure 1 shows that the short-term spillover level is significantly greater than the long-term spillover level, and the long-term spillover level is close to 0 most of the time, illustrating that the spillover effect in the "CCM – high-carbon-emission industries" network in the time domain lasts less than 3 months, but the spillover effects have little effect after 3 months. Overall, the total spillover index in this network shows different stages of change over time, and its time-varying trend is influenced mainly by policy, the macroeconomy and other factors. In 2014–2015, the stock market in China was in a bull market phase, and in 2015, the stock market continued to fall due to the previous irrational rise of the stock market, which created a large bubble; thus, the central government adopted deleveraging and tightened financial regulation to regulate stock market risks. Thus, due to the volatility of macroeconomic conditions, the total spillover index reached an extreme value between 2014 and 2015, followed by a

TABLE 5 Total spillover effects in the long term (longer than 3 months).

	CCM	CPI	CSI	CCI	From
CCM	11.33	3.30	3.05	0.89	7.24
CPI	1.06	3.97	3.54	4.25	8.85
CSI	1.12	4.05	3.68	4.35	9.52
CCI	0.92	1.70	1.70	5.66	4.32
TO	3.10	9.05	8.28	9.49	TCI
Net	−4.14	0.20	−1.24	5.17	7.48

Note: TO represents the spillover index, which indicates the spillover effect of a variable on all the other variables; FROM represents the inflow index, which represents the spillover effect received by a variable from all the other variables; and NET is the difference between the spillover index and inflow index, which indicates the net spillover effect of a variable on all the other variables. A value greater than 0 means that the variable is a net exporter; otherwise, it is a net recipient. TCI denotes the total spillover index, which represents the average of all the variables' spillover or inflow indices.

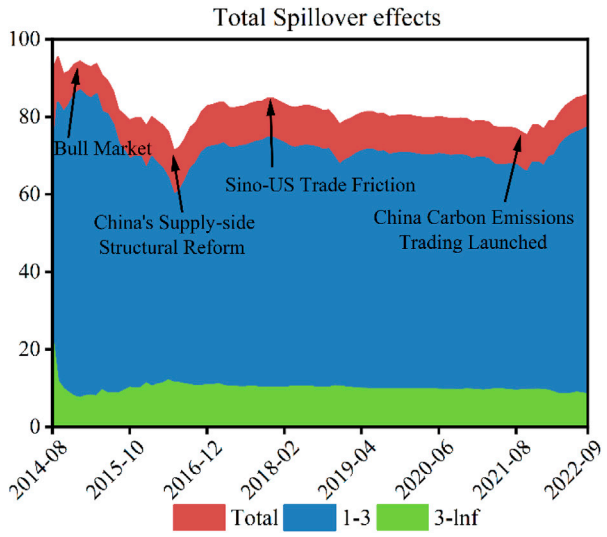


FIGURE 1
Total Spillover effects.

gradual decline from 2015 onwards. The second half of 2016 ushered in a period of supply-side reform and the use of market-based solutions to address overcapacity, so the overall spillover index rose again from the second half of 2016 onwards. In 2018, due to the continued escalation of the trade war between the United States and China and the continued depreciation of the RMB, the total spillover effect peaked in 2018 and remained relatively stable in subsequent years. The overall spillover effect in the network "CCM – high-carbon-emission industries" shown a considerable increase trend after the formal start of the China carbon emissions trading program in 2021.

4.2.2.2 Net spillover effect results

In Figure 2, we find that the CCM acts as a net exporter of short-term spillovers for most of the sample period, with its net spillover index value being positive for the vast majority of the time, while it is a net recipient in the long-term. This result implies that the CCM has a larger influence on the high-carbon-emission industries in the shrot term. Notably, the short-term spillover index of the CCM was negative in 2016, which may be related to China's supply-side structural reform and low trading prices and activity in the CCM.

The total spillover situation in the steel industry is almost the same as that in the electric power industry, both being net exporters of short-term spillovers for most of the sample period. However, the electric power industry acted as a net recipient of spillovers in both the short and long term between 2014 and 2015. Throughout the sample period, the cement sector received short-term spillovers, but in the long run, it was a net exporter of spillovers throughout the majority of the time. The net spillover indices for each market are vulnerable to unexpected events during the sample period. Examples include China's supply-side structural reform in 2016 and the trade conflict between China and the United States in 2018. It is evident that the spillover effects of all markets reach stage extremes under the influence of unexpected events. Moreover, the short-term and long-term net spillovers notably differ, and in the long-term frequency domain, the net spillovers in each market are relatively smooth and less volatile, reflecting that each market can digest market uncertainty information in the long term.

4.2.2.3 Net pairwise spillover effect results

To enhance comprehension of the interactive influential characteristics of the CCM and high-carbon-emission industries, the net pairwise spillover effects between the CCM and these industries are once again examined in the following from the standpoint of the frequency domain Figure 3.

(i) Show that the short-term spillover effects of the CCM on the electric power industry and the steel industry reached extreme values in 2014–2015 but then declined rapidly. Until the second half of 2016, the CCM was a net recipient of the electric power and steel industries in the short term, and after the second half of 2016, the CCM affected the electric power and steel industries in the short term. The short-term spillover effects of the CCM on the electric power and steel industries in 2018 also reached extreme values in the short term in this phase. However, the CCM is a net recipient of the electric power and steel industries in the long-term throughout the sample period. Overall, the short-term spillovers between the CCM and the electric power and steel industries are greater than the long-term spillovers. This finding also supports, to some extent,

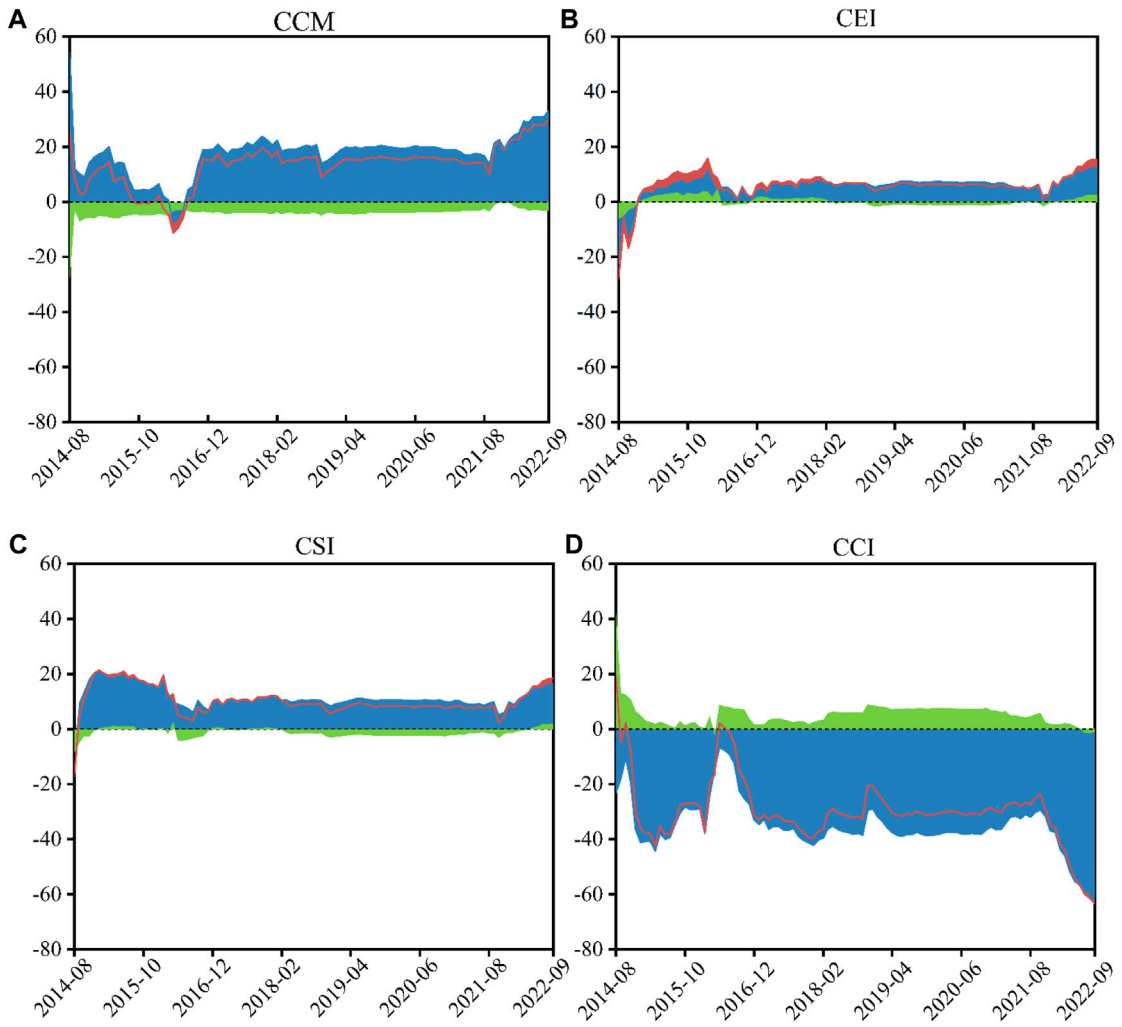


FIGURE 2
Net spillover effects.

the conclusions of Wang and Wang (2022). This paper argues that the extreme short-term spillover effects of the CCM on the power sector and the steel sector in 2014–2015 arose because of the influence of financial speculative factors in the stock market. Before the second half of 2016, the CCM affected the electric power industry and the steel industry mainly because the CCM at establishment was still incomplete, and after the supply-side structural reform in 2016, the CCM developed, so that the influence on the steel industry and electric power industry gradually strengthened in the short term. Moreover, the trade war between China and the United States in 2018 intensified the influence of the CCM on the sectors of steel and electric power in the near term. The findings of the previous analysis on the net spillover impact are validated by this as well.

(ii) As shown in Figure 3, the CCM had a significant impact on the cement industry in the short term during 2014–2015, but in the long term the cement industry had a significant impact on the CCM. After 2015, the cement industry was a net recipient of the CCM in both the short and long term. The chart clearly shows that the CCM spillover impact on the cement sector is considerably influenced by extreme occurrences.

(iii) A comparison of the above graphs shows that the electric power and steel industries had a significant impact on the CCM before 2016. This is because the was initially incomplete. In the early stage of operation, market liquidity was insufficient, price signal distortion and other problems occurred, and the price signal of the CCM could not truly reflect the demand and supply of carbon emission permits. Changes in the price of carbon emissions cannot significantly impact the production decision-making of enterprises, and enterprises lack active emission reduction incentives. Moreover, it is clear from the figure that the impact of the CCM on the cement industry in the short term is significantly greater than that on the electric power and steel industries. The paper

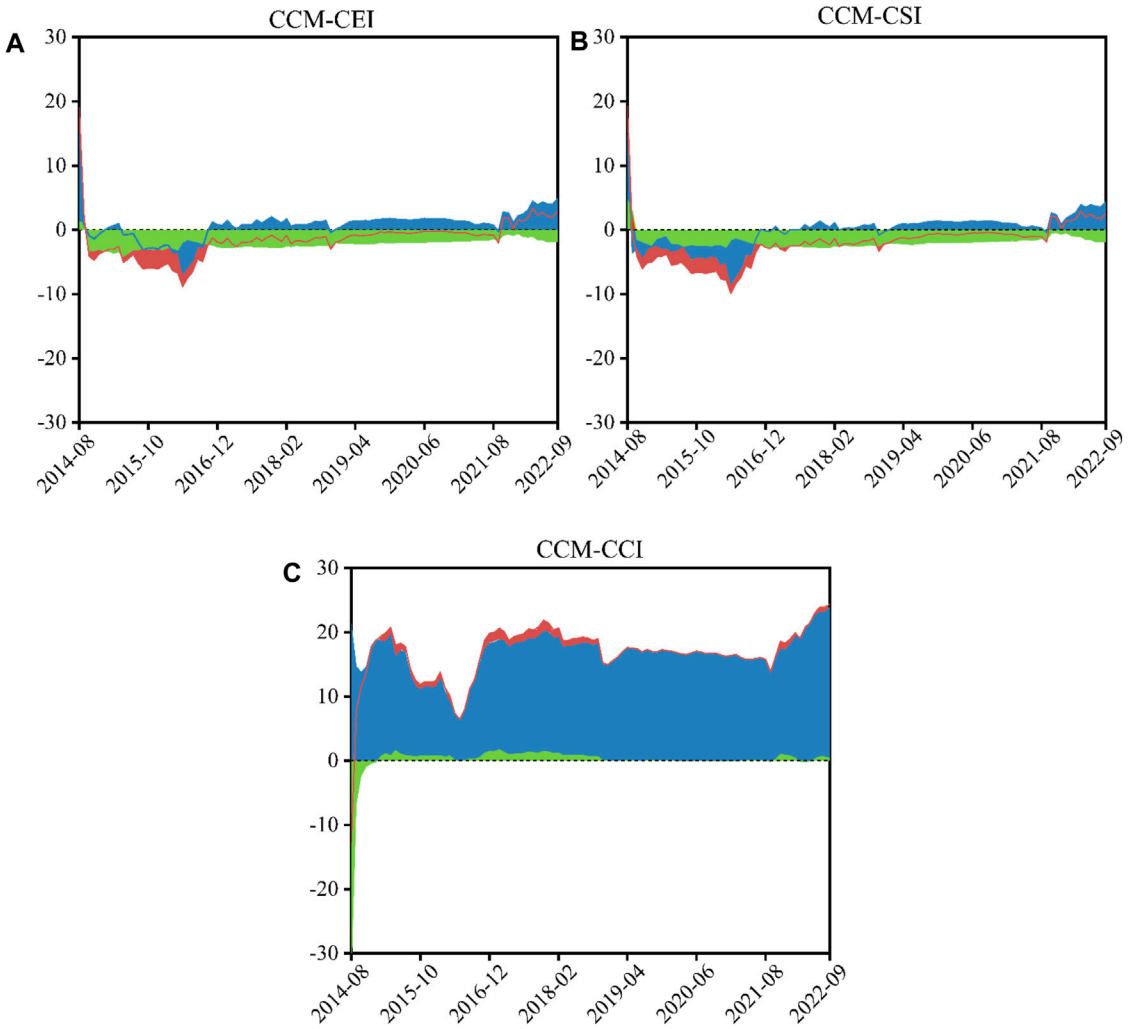


FIGURE 3
Net pairwise spillover effects.

suggests that this may be due to the relatively high carbon intensity of the cement industry's production process. Cement production involves the calcination of limestone at high temperatures, a process that releases large amounts of carbon dioxide. Since this chemical reaction is inherent in cement production and limestone is difficult to replace as a raw material, the cement industry faces a greater challenge in reducing carbon emissions. Secondly, the cement industry may be relatively lagging behind in emission reduction technologies compared to the power and steel industries. The power industry has more choices and greater flexibility in emission reduction technologies, and the steel industry can also reduce carbon emissions by improving production processes, using low-carbon raw materials and recycling waste gas. The cement industry, on the other hand, may find it difficult to find cost-effective and technically feasible abatement options in the short term, and is therefore more susceptible to price fluctuations in the carbon market.

4.2.2.4 Dynamic spillover network analysis of CCM and high-carbon-emission industries

The above examined the spillover effect between carbon market and high-carbon-emission industries from the perspective of frequency domain based on static and dynamic analysis, and in order to further clarify the dynamic change characteristics of volatile spillover among variables, and to demonstrate the risk contagion paths between carbon market and high-carbon-emission industries and the change of contagion paths under the influence of typical events, this paper examined the spillover network during the bull market in 2015 (August 2014–June 2015), the spillover network during the U.S.-China trade friction (January 2018–November 2019) and after the official start of the national carbon emissions trading (July 2021-end of the sample period).

Figures 4–6 report the short-term and long-term networks of the "Carbon Market - high-carbon-emission industries" system in the time domain as well as in the frequency domain under three special time periods:

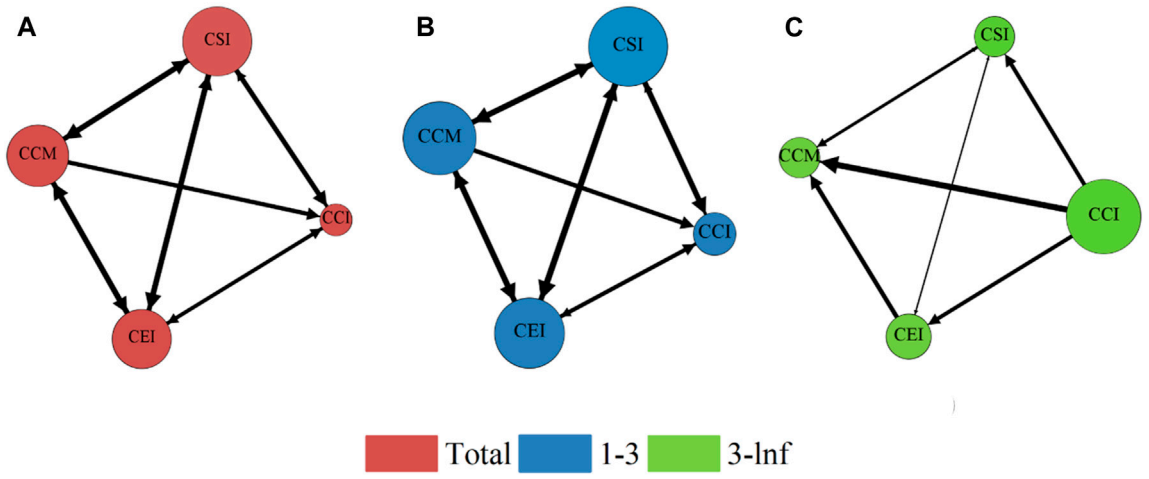


FIGURE 4
Network spillover during bull market.

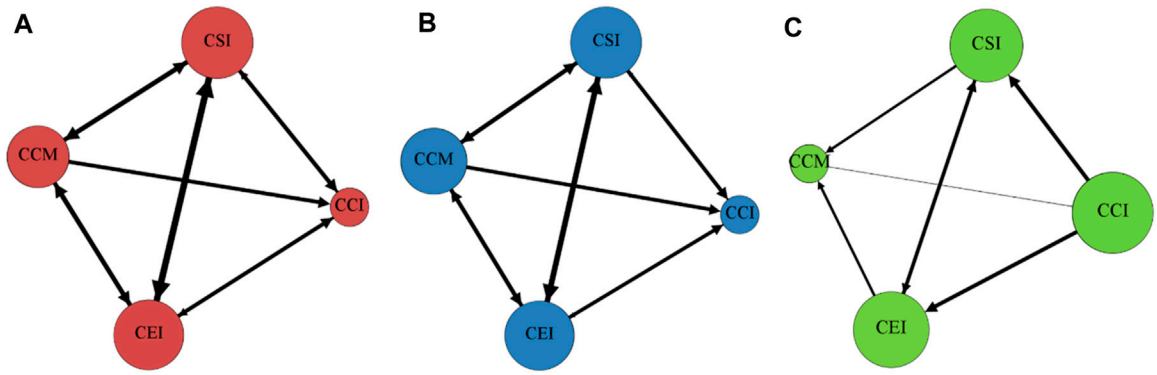


FIGURE 5
Network spillovers during US-China trade friction.

(i) In terms of the structural characteristics of the spillover network, the spillover networks under the three special event segments are basically the same, but the structural characteristics of the time domain and the short-term network are obviously different from those of the long-term network. From this, it can be seen that in the system of "CCM – high-carbon-emission industries", the short-term and long-term have different transmission paths, and the positions and roles of each node in the spillover network are not the same.

(ii) Under the three special event segments, the steel industry is the information leader in the time domain and in the short term, and the spillover effect on other markets is the largest. This may be due to the high sensitivity of the steel industry to changes in the economic environment. During bullish phases, when economic growth is expected to be strong, demand for steel increases, and industry sentiment rises, the market performance of the steel industry tends to foreshadow the overall market trend. During the U.S.-China trade war, steel as a key raw material, its price fluctuations are directly affected by trade policies, which in turn affects the cost and profitability expectations of the relevant markets. And after the opening of the carbon trading market, the cost of carbon emissions from the steel industry became the focus of market attention, and its dynamics directly affected the supply and demand and price fluctuations in the carbon market.

(iii) Whether in the time domain or in the short term, there is a significant spillover effect of the carbon market on high-carbon-emission industries, while in the long term the spillover effect of the carbon market on high-carbon-emission industries is small. This is also consistent with the conclusions drawn in the spillover analysis above, and further supports the points made above.

4.2.2.5 Study of the impact of EPU on volatility spillovers between CCM and high-carbon-emission industries

Thus, in order to better understand how EPU influences volatility spillovers between the CCM and high-carbon-emission industries, this paper employs Balcilar et al. (2016)'s nonparametric

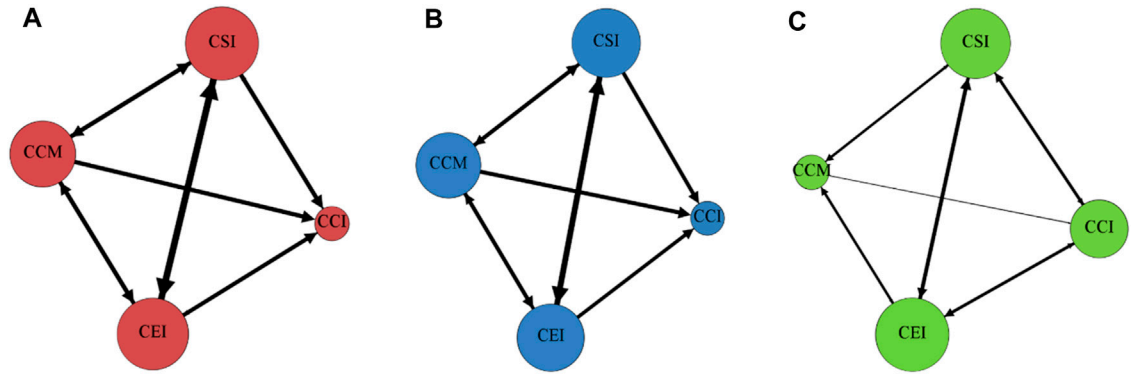


FIGURE 6
Network spillovers during the official start of China carbon emissions trading.

TABLE 6 BDS test.

Spillover series	Dimension				
	2	3	4	5	6
Total spillover	0.0400***	0.0803***	0.1176***	0.1424***	0.1611***
Total spillover in short-term	0.0327***	0.0812***	0.1273***	0.1592***	0.1821***
Total spillover in long-term	0.0796***	0.1388***	0.1970***	0.2374***	0.2605***
Net spillover between CCM and CPI	0.0219**	0.0380**	0.0698***	0.0848***	0.0916***
Net spillover between CCM and CPI in short-term	0.0531***	0.0772***	0.1055***	0.1170***	0.1150***
Net spillover between CCM and CPI in long-term	0.0618***	0.1248***	0.1575***	0.1676***	0.1705***
Net spillover between CCM and CSI	0.0554***	0.0940***	0.1267***	0.1406***	0.1376***
Net spillover between CCM and CSI in short-term	0.0520***	0.0868***	0.1184***	0.1305***	0.1308***
Net spillover between CCM and CSI in long-term	0.0700***	0.1319***	0.1634***	0.1708***	0.1664***
Net spillover between CCM and CCI	0.0714***	0.1101***	0.1342***	0.1332***	0.1260***
Net spillover between CCM and CCI in short-term	0.0424***	0.0732***	0.1098***	0.1272***	0.1342***
Net spillover between CCM and CSI in long-term	0.0979***	0.1628***	0.1932***	0.2122***	0.2296***

quantile Granger causality test to examine the causal relationship between EPU and both total and net pairwise spillovers.

Before studying the nonlinear effect link between EPU and volatility spillovers between the CCM and high-carbon-emission industries, it is first necessary to clarify whether there is a nonlinear structure between the two. In order to filter out the linear influence of the volatility spillover between EPU and the CCM and high-carbon-emission industries, this research uses the Broock et al. (1996) BDS test to design a VAR model. It then extracts the residuals for testing. The Table 6 displays the findings. The nonparametric quantile causality test may be performed as, as the Table 6 shows, all residual series are able to reject the initial hypothesis.

The findings of the nonparametric quantile causality test of the volatility spillovers between the EPU and the CCM and high-carbon-emission industries are shown in the Figure 7. First, the study demonstrates that at most quantile levels, EPU has an impact on both the total and net pairwise spillovers between the CCM and the high-carbon-emission industries. Additionally, it also demonstrates a greater correlation between EPU and volatility spillovers from carbon markets to high-carbon-emission industries. Furthermore, the figure indicates that the overall spillovers and net pairwise spillovers within the network of the "CCM – high-carbon-emission industries" are particularly susceptible to the influence of EPU when it is at the mid-quartile level. Basu and Bundick (2017) find declines in production, consumption, investment and employment time under uncertainty shocks. Therefore, economic policy uncertainty leads to a reduction in the supply of money in the financial market, which may trigger liquidity risk in the financial market, which in turn affects the supply of allowances in the carbon market, which leads to changes in the production, research and development (R&D) management of high-emission carbon-based industries, etc., which in turn causes changes in the level of production

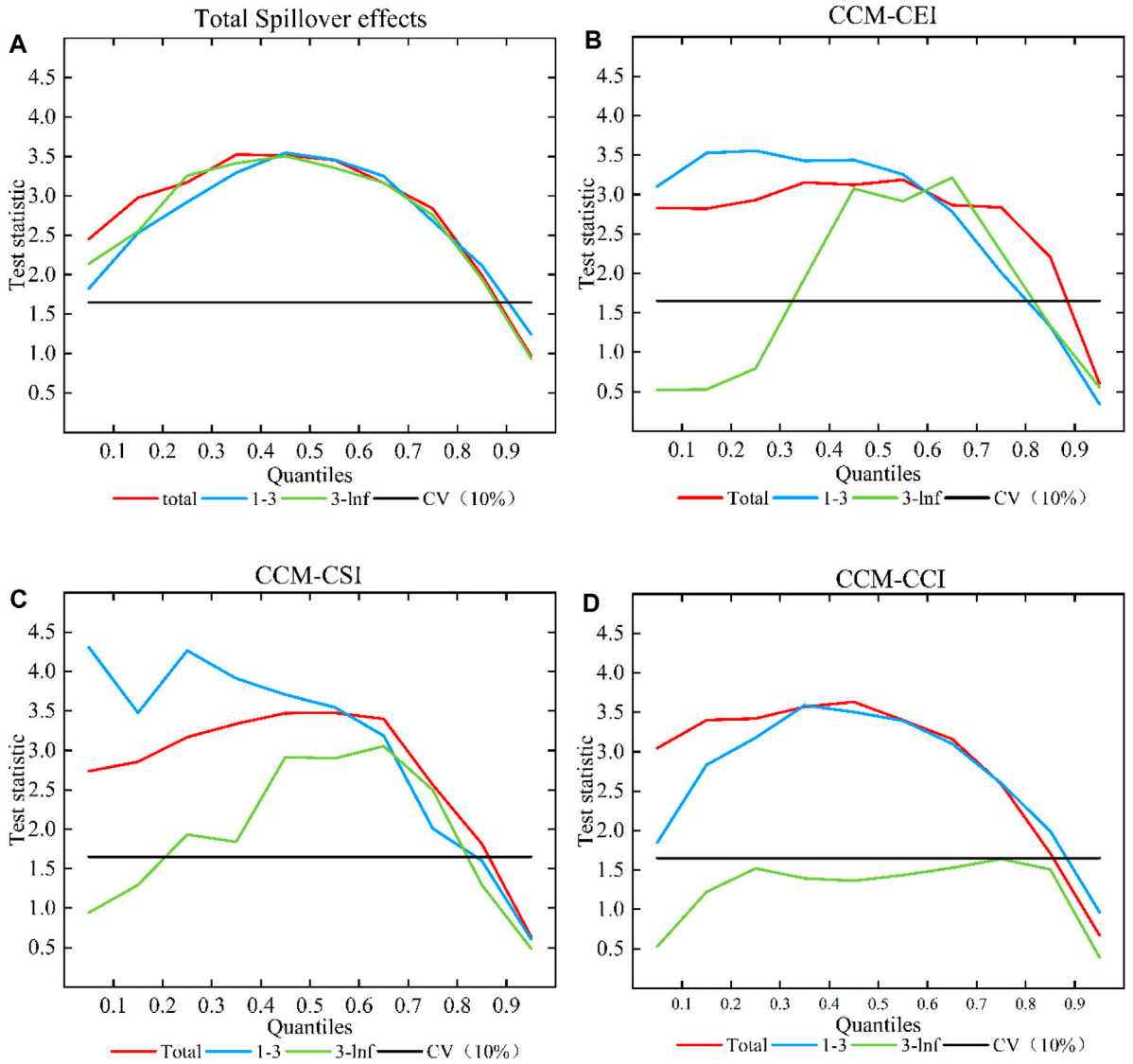


FIGURE 7
Causality-in-quantiles test results.

technology, and the price of products. Total spillovers and volatility spillovers between the CCM and high-carbon-emission industries are not greatly impacted by EPU at the low quantile level; moreover, they are even less affected by EPU at the high quantile level. The limited impact of EPU on volatility spillovers between the CCM and high-carbon-emission industries is due to the fact that producers in high-carbon-emission industries are capable of making rational decisions when market volatility is low, whereas they are driven by extreme pessimism or optimism when market volatility is high.

5 Conclusion and policy recommendations

The advancement of the carbon market under the background of global warming is receiving increasing amounts of attention from all countries, so it is urgent to address the problem of carbon emissions from high-carbon-emission industries. Nevertheless, there has been limited scholarly focus on the risk spillover effects from the CCM and high-carbon-emission industries, specifically in relation to the frequency domain. Consequently, in order to examine the spillover impact between the CCM and high-carbon-emission industries from a frequency domain perspective, this research first uses the BK spillover index, which was built based on the TVP-VAR model. Second, this research comprehensively examines the influence of EPU on the spillover effects between the CCM and high-carbon-emission industries in order to further explore the relationship between the two.

First the study found that “CCM – high-carbon-emission-industries” have much higher short-term spillovers than long-term spillovers. In addition, there are strong risk spillover effects between the CCM and high-carbon-emission industries. In the short term, carbon markets are mostly net exporters of spillovers;

however, in the long term, they are more susceptible to shocks from high-carbon-emission industries. Second, while the carbon emissions and intensity of the steel and electric power sectors are considerably higher in comparison to the cement industry, the short-term repercussions of the carbon market on the cement sector are considerably more pronounced. This demonstrates that the CCM is insufficient to drive the electric power and steel industries. As a result, in order to achieve a low-carbon and environmentally sustainable economic transformation, greater emphasis should be placed on the interconnections between the CCM and the steel and electricity sectors, in order to direct and incentivize businesses to conserve energy and decrease emissions. Third, the spillovers between the CCM and high-carbon-emission industries are significantly affected by EPU, and the effect is typically asymmetric; i.e., at the mid-quartile level, EPU is more likely to have an effect on the spillovers between the CCM and high-carbon-emission industries, while at the extreme-quartile level, EPU's effect is not obvious.

The foregoing conclusions lead this study to the following suggestions:

(i) For high-carbon-emission industries, with the improvement and development of the CCM, the influence of the CCM on these industries is becoming increasingly important. Therefore, high-carbon-emission industries should actively set emission reduction targets, promote enterprise transformation and upgrading, and realise green development to reduce the risk of losses they may bear in the process of carbon market development.

(ii) Regarding decision-making, the current carbon reform of the electric power and steel industries is insufficient, so special attention should be given to the coverage of the electric power and steel industries. In the meantime, the range of industries included in the CCM should be expanded further, gradually including building materials, chemical, petrochemical, nonferrous metals, and other high-carbon-emission industries, in order to improve the coverage of carbon emissions. At the same time, from the perspective of dynamic spillover network, we should be alert to the risk transmission of high-carbon-emission industries, identify the center of the network, and effectively supervise the key nodes to reduce the probability and scope of individual risk transmission.

(iii) For investors, it helps them to save risk management costs and improve risk prevention and control awareness. For example, market participants should be especially aware of the effects of changes in EPU when the spillover level between the CCM and high-carbon-emission industries is at the middle quartile level.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JH: Formal Analysis, Funding acquisition, Methodology, Software, Supervision, Writing–original draft. QS: Conceptualization, Data curation, Visualization, Writing–review and editing. YJ: Data curation, Software, Visualization, Writing–review and editing.

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Conflict of interest

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Sustainability materiality of insuring coal businesses for insurers

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This study aims to understand the impact of sustainability efforts on materiality or financial performance of insurers by accounting their risk coverage pattern in the Coal Mining Industry. 10 major insurance companies have been selected for this study and the focus has been to understand the stances and policies implemented by these companies between 2018 and 2023. Some of the firms like Hartford have officially declared that they have exited from this industry, while major players are still fueling the coal mining industry. Alternatively, companies themselves are looking to fund their risk mitigation plans so as to not rely on insurance firms. Studies by Hinshaw Law show that losses arising from climate change are rising at an alarming rate, the question then remaians, would insurance companies continue to fund activities that would put their existence in peril. Further research can be conducted on a larger time frame, new policies and frameworks implemented across this industry and to understand the risks of insuring activities that have increased the rate of climate change.

KEYWORDS

ESG, insurance, sustainability, coal industry, climate change

1 Introduction

Global warming and climate change are increasingly affecting human life in today's world. A US consensus shows that 3 in 4 Americans agree that it is human activity leading to this phenomenon (Thompson, 2019). The earliest studies on this phenomenon were done in the 19th century. Scientist Joseph Fourier hypothesized that carbon emissions would lead to global warming, as emitted CO_2 remains within the atmosphere due to some gases creating a heat trap (Fleming, 1999). In another article, Foote (1856) was able to find how and what gasses were causing heating and predicted a higher temperature for earth. In 1988, modern work on climate change started garnering attention as NASA scientist Hanses addressed the Congress on discovering evidence that global warming has begun (Shabecoff, 1988).

In recent times many political and economic pacts and treaties have been formulated. However, these pacts have not effectively translated into reduced emissions and/or better synergies for businesses. A report from the National Bureau of Economic Research points out that it is difficult to note the effects of climate change as it is difficult to map the different effects of global warming which makes it difficult to plug into an economic analysis, CO_2 emissions are a global phenomenon that have local effects and the consequences of which will only be seen in the distant future (Rossi-Hansberg, 2021). A recent report on global risks states that by 2034 long term potentially irreversible climate change would occur as a result of breaching the threshold and we would see a 3° degree world (WEF, Marsh McLennan and Zurich Insurance Group, 2024). Although, the economic impact cannot be accurately computed, businesses and their stakeholders today are exposed to all the effects of the environmental changes.

Practices to mitigate and address these risks have been put to use since years. In as early as 2004, a UN report titled "Who Cares wins" formalized ESG and encouraged its reporting (ABN Amro, Aviva, AXA Group, Banco do Brasil, Bank Sarasin, BNP Paribas, Calvert Group,

CNP Assurances, Credit Suisse Group, Deutsche Bank, Goldman Sachs, Henderson Global Investors, HSBC, Innovest, ISIS Asset Management, KLP Insurance, Morgan Stan, 2004). Since then, awareness around sustainable practices have been increasing and businesses have come under a lot of pressure to ensure that they are sustainable, social and generally "good" for the society.

Financial institutions are pressured to invest only in sustainable practices as society believed that these stakeholders could make an impact on sustainable practices of businesses. In 2017, there was massive backlash against American insurance companies for insuring fossil fuel companies. Environmental groups believed that financial institutions underwriting these practices were one of the major reasons that these organizations continued their activities (Bosshard, 2017). Insurers also need to mitigate climate change to ensure that they remain financially relevant in the long run especially since 44% of world carbon emissions come from Coal, naturally insurance companies need to reconsider their exposure to the industry. A report from 2023 shows that AIG, Liberty Mutual, Lloyd's of London, Swiss Re, and Zurich insure 41% of US Coal Mines (Mary Sweeters, 2023). Many insurers including Aviva and Alliance have limited their coal exposure while AXA promised a total exit from underwriting coal by 2030 (Distinguished, 2021).

There is a dearth of research that explores the area of sustainability practices of insurers and the financial impact on them. Therefore, this research aims to understand the impact of sustainability practice related coal underwriting by insurers and its impact on ESG scores. The study will further explore the impact on the financial performance of the insurers as coal underwriting make up to 1/3rd of the firm's earnings today.

This research will be useful to insurance industry to understand the impact of sustainability initiative on ESG scores and on the firm's financial performance. As several insurers stayed away from insuring new coal business which in turn created good corporate image for these insurers; it is important to see if that translated into better financial performance or materiality is impacted or not.

2 Literature review

Insurance cycles are an important factor that needs to be considered while understanding the operating decisions that these institutions tend to make (Doherty and Garven, 1993). Underwriting cycles tend to have an impact on the firm's solvency as they are influenced by market forces (Trufin et al., 2009). As changes in interest rates have a significant impact on the insurer's capital structure, the ripple effect will be seen on how the insurer would expose themselves to the different risks and the decisions they would partake to ensure a green bottom-line (Taylor, 1991).

With the gradually increasing environmental risks of the world reaching a point of no return and being catastrophic, there would be massive disruption of supply chain, manufacturing technologies and production cycles. Studies on SME activities have showed that uncertain environmental issues will disrupt their growth (Raar, 2015) and sustainable business practices need to be employed at the earliest (Morrad, 2020). The onus on ensuring that the world does not tip over lies with businesses and governments. Analysis by Brogi et al. (2022) reveals that the social and environmental pillars of ESG have a stronger impact on financial performance compared to the governance pillar in general. Additionally, firm-specific characteristics like solvency, profitability, and size are found to be significant determinants of ESG awareness (Bressan, 2023a,b). Incentivizing businesses to reduce their carbon footprint is essential and investors are making mindful decisions based on the disclosures and available ratings for said firms (Jinga, 2021). These decisions also impact the market sentiment towards financial institutions.

Incidentally, it is becoming increasingly important for insurance companies to communicate their stand on sustainability to ensure a positive reputation. Okhrimenko and Manaienko in their research on life insurance companies' reputations in Ukraine (2019) proved that insurance firms need to strengthen their corporate social responsibility and provide high quality information to have the trust of stakeholders (Okhrimenko, 2019). ESG disclosures have shown a positive impact on a firm's financial performance. Specifically, the environmental dimension is shown to have a positive relationship with a firm's stock price and return on capital (Raisa Almeyda, 2019). In a study conducted by Khovrak (2020), 156 insurance companies were compared by the level of ESG risk they pose and their geographical affiliation. The study identified some common guidelines in framing a report and in companies' approach to ESG components (Khovrak, 2020). However, it is also evident that a companies' reputation and financial standing and have been impacted by other factors as well including but not limited to new product launches, price wars and marketing strategies. These have made it difficult to understand the impact of their sustainability practices on their financial performance.

Growing ESG concerns pose a looming threat to insurance companies across all operating domains. However, research connecting insurance to ESG values are few. A few studies have tested the relationship between ESG and an insurance firm's financial indicators. Silvia Bressan in her research on the effects of ESG scores on P&C Insurance companies concludes that ESG scores have a significant impact, and a high ESG insurance firm is said to be financially stronger although exposed to the risks of underwriting (Bressan, 2023a,b). Another study focusing on American insurers between 2006 and 2018, provides evidence of a positive correlation. These studies demonstrate that higher ESG scores are associated with a decrease in financial distress, suggesting that sustainability practices contribute to enhanced financial stability for insurance companies (Chiaramonte et al., 2020).

Sustainable practices in the insurance industry have proven to be better for insurance companies specifically practicing in the life insurance sector. Insurers that adopt a more long-term approach and are conscious of their actions have better social scores, thereby increased trust amongst stakeholders (Chiaramonte et al., 2020). However, the nature and extent of understanding the impact of sustainability practices on a firm's financial situation is considered to be complex and is debated about by many authors (Agnieszka Herdan, 2020).

A link is observed between sustainability and the purchase of reinsurance (Atz et al., 2023). As suggested in the research conducted by Atz companies with high ESG scores tend to be more profitable and engage in less reinsurance, suggesting they may have applied appropriate risk mitigation strategies leading to potential cost savings. The relationship between environmentally sustainable firms and their profitability is positive (Ki-Hoon Lee, 2016). However, the financial performance of a firm does not have any significant impact on a firm's

TABLE 1 List of insurance companies.

Companies in this study	
AIG	Zurich
Chubb	Swiss Re
Axis Capital	Travelers Insurance
The Hartford	Old Republic
Generali	Allianz

sustainability. For example, Berkshire Hathway, Starr and Liberty Mutual are amongst the biggest names in the insurance industry that are still underwriting new coal projects (Insure Our Future, 2022) even though there is significant research stating the enhanced environmental and financial risks of persistent support provided to the fossil fuel industry (El Safty and Siha, 2013).

Through these various research dimensions, we see the complexity of insuring coal businesses. Considering profits in the present or delayed gratification which is not guaranteed is the question that all investors face. We delve deeper into understanding the impact of insurance firms taking a stance on this dilemma mentioned and its effects on the financial performance and reputation of insurance firms.

3 Methodology and data collection

Insurance companies that are currently operating in the American coal mining industry have been selected for this study. Of these there are few companies that have decided to phase out of underwriting coal projects in the coming years and ones that have no stance on whether they will be phasing out of the industry. Table 1 illustrates the companies chosen for this study.

AIG, Chubb, Axis Capital, Zurich, The Hartford, Generali, Swiss Re, Travelers Insurance, and Allianz have issued statements on phasing out of underwriting coal projects. Careful study of the companies transcripts have been conducted (Gunnar Friede, 2015; Axis Capital, 2018, 2019, 2020, 2021, 2022, 2023; Chubb, 2018, 2019, 2020, 2021, 2022, 2023; Generali, 2018, 2019, 2020, 2021, 2022; Old Republic, 2018, 2019, 2020, 2021, 2022; AIG, 2018a,b, 2019a,b, 2020a,b, 2021a,b, 2022a,b, 2023; Allianz, 2018a,b,c, 2019a,b,c, 2020a,b,c, 2021a,b,c, 2022a,b,c; Hartford, 2018a,b, 2019a,b, 2020a,b, 2021a,b, 2022a,b; Swiss Re, 2018a,b, 2019a,b, 2020a,b, 2021a,b, 2022a,b, 2023; Agnieszka Herdan, 2020). However, there are many cases in recent past showcasing some of these companies underwriting major coal projects in the United States (Insure Our Future, 2023). Some big insurance firms that are part of a conglomerate, like Berkshire Hathway have businesses in fossil fuels including coal mining. Due to the complexity of their own structure and vested interests of the group; these companies have not taken a stance on underwriting coal projects (Berkshire Hathaway, 2024).

A comprehensive study of the sustainability practices of the companies in reference to coal underwriting and its impact on the financials of the firm is studied. Variables net written premium, net income, expense ratio, combined ratio, total risk (standard deviation), average returns and volatility of stock prices are considered. A qualitative analysis of the reports and latest ESG scores are analyzed to understand the underlying relationship between all the variables.

TABLE 2 Net written premium.

Company	2022	2021	2020	2019	2018
AIG	25,512	25,890	22,959	25,092	26,407
Chubb	41,755	37,868	33,820	32,275	30,579
AXIS Capital	4,734	4,926	4,336	5,709	5,766
Hartford	11,158	10,041	8,969	8,452	7,136
Travelers	35,414	31,959	29,732	29,151	27,708
Old Republic	39,782	36,809	34,313	34,690	33,804
Zurich	47,101	44,806	40,567	41,251	41,230
Swiss Re	43,917	43,220	39,827	39,649	34,042
Allianz	93,001	84,776	82,333	81,987	78,497
Generali	28,476	24,170	22,559	22,017	21,267

All the data is collected from the annual reports of the firms and Yahoo Finance.

The net written premium is an indicator of the amount of business a company has done in the past year. It includes the sum of premiums written minus premiums ceded to reinsurance companies, plus any reinsurance assumed. The table shows us the net written premiums for the period between 2018 and 2022.

$$Net\ Premiums\ Written = Sum\ of\ Premiums\ written - \left(\begin{matrix} Premiums\ ceded\ to\ reinsurance \\ companies + reinsurance\ assumed \end{matrix}\right)$$

A firm's net income indicates its true earnings for a given year. It is the amount that is available to shareholders after all expenses have been catered to. The expenses include interest, taxes and deductions. It shows how effectively a firm is able to manage all its expenses (operating and non-operating). The table shows the net income of all the selected companies for this study. We can see that on average that companies are not performing consistently. One of the major reasons for this is the COVID-19 pandemic, which had a huge impact in 2020 as reflected in Tables 2, 3.

Table 4 showcases the expense ratio which is a percentage of premium used to pay for all the expenses towards acquiring, writing and servicing of insurance and reinsurance. It represents how efficiently a firm manages its operations. Smaller firm like Old Republic and Travelers have had a better control over their expenses in comparison to larger firms. On a trend we can see that all the companies have been reducing their expense ratios since its peak in 2020.

$$Expense\ Ratio = \frac{Underwriting\ expenses + Commissions}{Net\ Written\ Premium}$$

Combined ratio evaluates the profitability of an insurance firm (Insurance Training Centre, 2024). It can be viewed as, for every unit of premium earned, the firm has lost or paid out "x" units. This is expressed as a percentage and as a general rule it is believe that a percentage between 75 and 90% is considered optimum for an insurance firm. From Table 5, we can see that all the insurance firms have been maintaining a good ratio since 2020.

TABLE 3 Net income.

Company	2022	2021	2020	2019	2018
AIG	10,247	9,359	−5,973*	3,326	−6
Chubb	5,313	8,539	3,533	4,454	3,962
AXIS Capital	2,230	6,186	−1,204	−3,234	−4,307
Hartford	1,815	2,365	1,737	2,085	1,807
Travelers	2,842	3,662	2,697	2,622	2,523
Old Republic	6,864	15,343	5,586	10,564	3,705
Zurich	4,923	5,425	4,071	4,384	3,977
Swiss Re	472	1,437	−878	727	462
Allianz	7,757	7,673	7,133	8,302	8,319
Generali	3,612	3,843	2,439	2,884	2,494

*Inclusive of all verticals of the business.

TABLE 4 Expense ratio.

Company	2022	2021	2020	2019	2018
AIG	31.1%	31.6%	33.3%	34.4%	35.7%
Chubb*	48.6%	49.3%	56.6%	51.9%	51.4%
AXIS Capital**	14.2	16.2%	16.5%	18.3%	16.8%
Hartford	31.6%	32.2%	33.5%	34.7%	33.9%
Travelers	28.5%	29.4%	29.9%	29.6%	30.1%
Old Republic	27.4%	26.5%	25.6%	25.7%	25.0%
Zurich	30.6%	31.2%	32.0%	32.1%	32.4%
Swiss Re	28.1%	28.8%	29.1%	34.9%	34.3%
Allianz	26.8%	26.7%	26.8%	27.5%	28.0%
Generali	28.7%	28.2%	28.1%	28.4%	27.9%

*Loss and expense ratio for the general insurance line.
**Underwriting-related general and administrative expense ratio.

TABLE 5 Combined ratio.

Company	2022	2021	2020	2019	2018
AIG	91.9%	95.8%	104.3%	99.6%	111.4%
Chubb	84.6%	86.4%	95.4%	90.9%	90.5%
AXIS Capital	95.8%	97.5%	109.6%	102.6%	99.9%
Hartford	90.2%	95.8%	100.4%	97.7%	92.6%
Travelers	95.6%	94.5%	95.0%	96.5%	96.9%
Old Republic	89.5%	91.3%	95.5%	97.5%	97.2%
Zurich	94.3%	94.3%	98.4%	96.4%	97.8%
Swiss Re	93.1%	90.6%	115.5%	127.9%	117.5%
Allianz	94.2%	93.8%	96.8%	95.5%	94.0%
Generali	93.2%	90.8%	89.1%	92.6%	93.0%

$$Combined\ Ratio = \frac{Incurred\ Losses + Expenses}{Earned\ Premiums}$$

The stock prices for the same period have been considered to understand the perspective of the market on these stocks (see Supplementary Annexures). Tables 6–8 represent the annualized average returns, annualized total risk of the stock and volatility. These parameters help us in understanding how much these stocks have varied for the duration considered in the study, thereby how investors see the stock.

TABLE 6 Annualized average returns.

	2018	2019	2020	2021	2022
AIG	−36.51%	28.51%	−10.72%	45.49%	14.68%
Chubb	−10.43%	19.22%	4.93%	26.28%	15.40%
AXIS Capital	4.41%	15.89%	−5.34%	11.85%	2.43%
Hartford	−22.13%	32.52%	−11.82%	39.75%	11.70%
Travelers	−10.66%	14.79%	6.46%	12.58%	21.27%
Old Republic	−2.31%	8.92%	−6.68%	26.27%	1.28%
Zurich	−0.31%	31.24%	−2.41%	8.90%	12.09%
Swiss Re	−0.20%	19.71%	−18.79%	10.16%	−1.00%
Allianz	−7.02%	19.64%	0.12%	4.90%	0.34%
Generali	−2.07%	24.46%	−18.03%	28.28%	−7.20%

TABLE 7 Annualized total risk.

	2018	2019	2020	2021	2022
AIG	28.63%	19.95%	59.56%	30.25%	30.01%
Chubb	20.15%	9.56%	35.37%	26.99%	22.19%
AXIS Capital	19.91%	19.33%	47.04%	29.93%	25.53%
Hartford	16.16%	13.53%	43.32%	34.99%	22.77%
Travelers	19.56%	16.39%	28.95%	19.16%	26.45%
Old Republic	18.26%	10.49%	34.65%	29.63%	25.44%
Zurich	13.70%	10.49%	29.29%	20.60%	21.52%
Swiss Re	14.90%	13.55%	41.14%	21.85%	26.81%
Allianz	20.15%	17.24%	44.44%	18.17%	28.43%
Generali	20.32%	15.58%	39.46%	16.77%	30.66%

The consolidated ESG scores show the overall impact that the firm has with respect to Environment, Social and Governance aspects of a business. They indicate how well the firm has managed to perform on all these parameters. This data is sourced from Sustainalytics. Table 9 shows us the latest ESG scores of all the firms considered for the study.

4 Discussion and analysis

Insurance companies may face catastrophic damage in the future due to climate change (Marcacci, 2019). As stakeholders increase their concerns over ESG practices, companies have become more conscious of their marketed solutions. Thereby inexplicably, shifting the risks of sustainable practices on insurers.

Based on the data collected, we understand that there has been no significant impact on the financial performance of the insurers even though they have brought in new policies for phasing out of the coal industry. All the companies listed in this study have policy rules which pertain to them not insuring firms that are making a certain percentage of their revenue from thermal coal and coal projects AIG (2018b, 2019b, 2020b, 2021b, 2022b, 2023), Allianz (2018c, 2019c, 2020c, 2021c, 2022c), Chubb reports (all 5), Genrali reports (all 5), Hartford (2018b, 2019b, 2020b, 2021b, 2022b, 2023), Old Republic reports (all 5), Travelers

TABLE 8 Volatility.

AIG	0.37206
Chubb	0.24598
AXIS Capital	0.31198
Hartford	0.30402
Travelers	0.22608
Old Republic	0.26005
Zurich	0.21135
Swiss Re	0.27140
Allianz	0.28538
Generali	0.27219

TABLE 9 ESG scores sourced from Sustainalytics.com.

Company	ESG scores	
AIG	24	46th percentile
Chubb	24	43rd percentile
AXIS Capital	24	45th percentile
Hartford	17	16th percentile
Travelers	20	29th percentile
Old Republic	28	62nd percentile
Zurich	16	14th percentile
Swiss Re	16	14th percentile
Allianz	13	7th percentile
Generali	18	19th percentile

reports (all 5), Zurich Insurance reports (all 5). However, the commercial confidentiality clause makes it very difficult to identify which firms are actually implementing the policy (Wood, 2022).

Some firms like Hartford have exited all existing insurance relationships and investments in publicly traded securities in companies that exceed coal and tar sands related policy thresholds (Hartford, 2023). However, this has not had any significant impact on its financials nor in the stock market. The total risk of the stock remains high and returns average. AIG, Zurich, Chubb and Swiss Re which are some of the biggest insurers of US coal also do not see any significant negative impact because of these practices. This phenomenon, shows that there are no incentives for businesses to phase out of coal in the immediate timeline.

The combined ratio and expense ratios are in the same range for all the companies- they are profitable regardless of whether they insure coal or not. Expense ratios indicate the firm's expenses on acquiring a premium, the lower the number the more profitable a company is. This ratio in included in calculating the combined ratio as well, however for this particular study we have taken this (expense ratio) separately to indicate that regardless of the implementation of policies and a global pandemic all these companies have maintained their profitability. The companies also seem to have similar risk profiles and similar combined ratios. Interestingly so these insurance firms even in times of extreme duress across the world have not reported losses, which leads to question if they really implemented policies on phasing out of the industry. It will be impertinent to watch the outputs derived from these actions in the near future.

The stocks of all these companies too illustrate similar volatility. AIG's stock is more volatile than the rest but a direct connection between insuring coal and this volatility cannot be established. Especially since there are a lot of external factors that play a huge role in determining it. However, it can be inferred that this volatility shows investor and markets do not know how to react to the changing landscape and are eagerly awaiting more information.

On closely examining the sustainability reports of each of the firms, we see a consistent nod towards sustainability practices, but there is little to no mention about coal and related insurance in their recent reports. Out of the 10 firms selected in this study, 9 of them (as mentioned previously) have put restrictions on coal in the period under examination (2018–2020). There has been some impact of these restrictions as insurers are backing away from underwriting new coal projects and coal miners are forced to set aside millions of dollars to cover their risks (Mcfarlane, 2023). This development just shows that money is not moving out of the industry rather is being circulated through different means. It is also important to note that there is still a large amount of insurance coverage for the coal industry and as seen in the data collected, there is no incentive for these companies to phase out completely.

Although, there is no incentive for firms to exit this sector immediately, there is rising concern over the increased risk of calamities. The Geneva Association Task Force in its report has outlined that if climate change is left unmitigated, the negative impacts will significantly increase and severity and frequency of various "perils" (earthquakes, hurricanes, viruses, wildfires etc) will also significantly increase (The Geneva Association Task Force, 2021). This will lead to newer challenges including population shifts - which is already visible in states like Arizona and Florida, where people are shifting for more affordable housing, lesser cost of living and more job opportunities at the risk of their security. Strategically, it is not viable for insurance firms to completely exit this sector for this decade too. They benefit from the increased premiums, predictable risk profile and volatility in the political landscape. Many countries are undergoing elections this year, and increasingly the sentiment is positive towards political parties that are "far right." Meaning, people would like leaders who are more selfish in the policies that they make for the nation, leaders that are more nationalists than globalists.

5 Conclusion

There is a growing sense of urgency amongst all stakeholders to address climate change issues. Many believe that the continued support from the financial industry is what is still boosting climate change. While this maybe true, the shift from fossil fuel energy to more modern and ecofriendly energy resources needs to be supported by all stakeholders. Insurance firms need to change priorities and be more agile in adapting to the changing ecological landscape of today's world.

Companies like AIG, Swiss Re and Zurich are some of the biggest insurers of coal in the US despite net zero promises. Reports by Insure our future show that AIG is the biggest insurer, insuring about 28.1% of coal in the US, Zurich about 4.9% and Swiss Re insurers about 3% of the total output. Mary Sweeters of Insure our future is quoted saying "This damning report perfectly illustrates the problem: insurers are publicly committing to net zero emissions and restrictive fossil fuel policies, yet behind closed doors they continue to underwrite dirty fossil fuel

projects, violating their own policies or exploiting loopholes. They are fuelling the climate crisis and profiting from it, while greenwashing their business with empty promises" (Insure Our Future, 2023).

From the research, we understand that there seem to be no impact on the companies' financials even after they came out with policies on phasing out. The volatility of their stocks were high and there seems to be no significant impact on their ESG scores. (ESG scores include social and governance factors which could be driving the scores as well). Given that there is no immediate benefit that is tangible, insurance firms in their truest nature must be socialists to survive in the world, and for that to sustain and continue, immediate action is required.

However, in the current circumstances and market forces it is clear that insurance firms are not going to completely phase out as there seems to be no financial or reputational incentive to do so. Therefore, the stances taken and the measures adopted may be a way to put society at ease, while the firm continues to maintain its balance sheets. Also given the current research is limited in scope, there may be a few other factors that are influencing profitability to the business, this could be new market opportunities (the rise of climate change has exponentially increased the threat to property, life and casualty), cost cutting, and or changes in the market dynamics. The rise of climate change has invariably increased the risk to traditional business models and thereby to businesses, supply chains and operations continues. It is also predicted that an increased threat to the environment will cause higher losses for insurance firms. Therefore, their continued presence in the fossil fuel sector is counterintuitive to their sustainability. How long could this model continue to work is a question that only time can answer.

Considering that we still do not have a sustainable alternative for fossil fuels, and that there seems to be no immediate change in the climate landscape; at least for the short-term business landscape, this is even more reason for insurers to not move away from insuring coal businesses. Therefore, the evidence we find in this research and the risk profile for the short-term business landscape prove why these businesses are not moving away from this sector just yet.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MU: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Assessing the synergistic effect of "pollution and carbon reduction" and "economic growth": a perspective from bilateral trade between China and RCEP countries

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Introduction: With the accelerating process of globalization, trade activities have had profound impacts on both the environment and economic development.

Methods: This paper comprehensively evaluates the synergistic effect of bilateral trade on "pollution reduction" and "carbon mitigation," as well as "economic growth," utilizing panel data from China and RCEP countries spanning the period from 1997 to 2020.

Results: The empirical results reveal that bilateral trade significantly propels economic growth in RCEP countries and exhibits a positive "pollution reduction" effect, whereas its "carbon reduction" effect remains uncertain. To delve into the underlying reasons for bilateral trade's failure to effectively mitigate carbon emissions, this paper undertakes a mechanism test along two opposing paths. Notably, the influence of bilateral trade on economic growth and "pollution reduction" in RCEP countries varies regionally. Specifically, bilateral trade is more efficacious in fostering economic growth in ASEAN countries. Additionally, bilateral trade enhances environmental quality in ASEAN countries, yet it deteriorates in non-ASEAN countries. Furthermore, this paper examines the intricate relationship between bilateral trade, economic growth, and "pollution reduction" through the application of the PVAR model. It concludes that optimizing environmental quality in RCEP countries is conducive to both local economic growth and bilateral trade.

Conclusion: This study not only bears significant implications for understanding the complex interplay between economic growth, environmental quality, trade liberalization, and environmental policies, but also provides invaluable guidance for policy formulation and implementation aimed at achieving green transformation and fostering sustainable economic development.

KEYWORDS

bilateral trade, economic growth, environmental quality, carbon emission, RCEP

1 Introduction

The global economic landscape has been significantly impacted by the ongoing COVID-19 pandemic, with growth rates slowing across various economies. However, amidst this backdrop, bilateral trade between China and the members of the Regional Comprehensive Economic Partnership (RCEP) has demonstrated remarkable resilience and growth potential (Fang et al., 2022). As nations strive for economic revitalization and job creation through strategic measures such as investment promotion, innovation drive, and international cooperation, the nexus between economic growth and environmental sustainability has gained renewed significance (Li et al., 2023).

In recent years, the relationship between economic development and environmental quality has evolved from a perceived dichotomy to a mutually reinforcing one, with both objectives being achievable through innovative policies and practices (Li et al., 2020). China, as a global leader in climate action, has consistently emphasized green and low-carbon development as a strategic imperative for advancing ecological civilization and fostering sustainable development (Zhu and Lan, 2023; Bai et al., 2024). Despite the IEA's projection of a marginal increase in global CO_2 emissions from industrial processes and energy combustion in 2022, the rate of this growth remains lower than that of global GDP, signaling a modest improvement in energy-use intensity.

The international community has converged on the imperative of controlling pollution and carbon emissions, recognizing the severity of climate change and the urgency of addressing environmental challenges (Li and Li, 2020). Amidst this consensus, international cooperation has intensified, with agreements and mechanisms being formulated to jointly tackle climate change and enhance environmental stewardship (Schneider and La Hoz Theuer, 2019). The RECP, as one of the largest, most populous, and geographically widest-ranging free trade agreements in the world, not only aims to promote trade liberalization and economic integration among its member states but also holds the potential to deepen environmental cooperation and jointly address global environmental challenges. Hence, our motivation for selecting RECP countries as the subject of this study stems from the following aspects.

To start with, RECP member countries span economies in East Asia, Southeast Asia, and Oceania, which are interdependent in terms of economic development and face similar environmental challenges. Studying environmental cooperation among RECP countries can help reveal the positive impacts of regional economic integration on environmental governance, providing valuable insights for other regions. Then, while economic issues dominate the RECP agreement, member countries have also expressed their shared concern for environmental sustainability during the signing process. By examining environmental policy coordination and mechanism innovation within the RECP framework, we can gain insights into how to promote economic growth without compromising the environment, exploring green development models tailored to the region. Furthermore, the world is currently confronting grave environmental challenges such as climate change, biodiversity loss, and increasing pollution. As significant economies and natural resource users, RECP countries' environmental policies and practices significantly impact the global environment. By studying these countries, we can better understand how to foster global environmental cooperation and jointly tackle global environmental issues. Finally, RECP countries generally recognize and are committed to achieving the United Nations' 2030 Agenda for Sustainable Development, including numerous environmental-related goals such as environmental protection and climate action. By thoroughly analyzing RECP countries' efforts and achievements in pursuing these goals, we can provide valuable references and insights for other countries and regions, fostering sustainable development worldwide.

Given China's pivotal role within the RCEP and its substantial trade ties with other member nations, totaling 12.95 trillion yuan in 2022, a year-on-year increase of 7.5% and accounting for 10.7% of China's GDP (customs data), it is imperative to understand the multifaceted implications of bilateral trade for the region's environment and economy. Trade, as a catalyst for industrial development, technological advancements, and resource optimization, can propel economic growth while facilitating the dissemination of environmental protection technologies and best practices. This begs the question: Can bilateral trade between China and RCEP members achieve a harmonious balance between pollution and carbon reduction, on the one hand, and economic growth, on the other?

The motivation for this study stems from the pressing need to evaluate the intricate interplay between bilateral trade, environmental quality, and carbon emissions within the RCEP framework. By investigating this relationship, we aim to contribute to the following objectives: Firstly, providing a nuanced assessment of the environmental and economic implications of regional economic integration. Secondly, exploring the role of bilateral trade in mitigating pollution and carbon emissions across diverse economic and social contexts, thereby enhancing our understanding of trade-related channels and mechanisms for environmental protection. Thirdly, through a heterogeneity analysis, we seek to discern the differential impacts of bilateral trade on ASEAN and non-ASEAN countries, informing the formulation of targeted policies. Lastly, employing the Panel Vector Autoregression (PVAR) model to analyze the dynamic interactions among bilateral trade, environmental quality, and carbon emissions offers critical insights for fostering a positive synergy among these variables.

Moreover, this study contributes to the existing literature in several novel ways. Firstly, it fills a gap in the research on the environmental impacts of bilateral trade within the context of mega-regional free trade agreements, specifically the RCEP, which has yet to be thoroughly explored. Secondly, by focusing on both ASEAN and non-ASEAN member countries, our study offers a more comprehensive analysis of the differential impacts of bilateral trade on environmental outcomes across diverse economies and social contexts. Thirdly, the application of the PVAR model allows for a dynamic and intertemporal examination of the relationship between bilateral trade, environmental quality, and carbon emissions, providing a more nuanced understanding of the complex interactions among these variables. Finally, our findings offer practical implications for policymakers in RCEP countries, as well as other regions contemplating similar trade agreements, by highlighting the potential benefits and challenges associated with

promoting economic growth while safeguarding environmental sustainability.

The structure of this paper unfolds as follows: Section 2 delves into the literature review and theoretical framework, Section 3 outlines the methodology and data sources, Section 4 presents the empirical findings and discussions, and Section 5 concludes with policy implications and future research directions.

2 Literature review and theoretical analysis

The implementation of RCEP in China has strengthened economic ties and cooperation with other members, promoted trade and investment liberalization, and thus driven economic growth and industrial upgrading (Chen and Chen, 2021). On the one hand, RCEP will reduce tariff and non-tariff barriers as well as trade costs among members, and simplify trade procedures and standards, making China's goods and services more competitive, stimulating export growth and import diversification (Peng et al., 2022). On the other hand, RCEP provides Chinese enterprises with broader market access opportunities in other members' markets (Zhang et al., 2023). In addition, enterprises from other members will have easier access to the Chinese market, which will expand the size of bilateral trade and encourage the growth of imports and exports. In addition, enterprises from other members will have easier access to the Chinese market, which will expand the size of bilateral trade and encourage the growth of imports and exports. So, is the bilateral trade between China and RCEP members effective in "reducing pollution and carbon emissions" and "economic growth"? From the existing literature, this article explains the following two aspects.

2.1 Bilateral trade and economic growth

With the continuous deepening of international relations and economic integration, the relationship between trade openness and economic growth has become a hot topic of concern. From existing literature, the conclusion that trade openness contributes to economic growth has been supported by numerous studies (Schneider, 2005; Ma et al., 2019; Arvin et al., 2021; Zhuang et al., 2022). Trade openness can enable enterprises to gain broader markets, increase sales opportunities and potential consumers, and foster production and investment activities (Tiwari et al., 2022). At the same time, trade openness can also introduce more advanced products and technologies, increase production efficiency and competitiveness, thus helping to optimize resource allocation and facilitate economic efficiency (Chang et al., 2009). As economic globalization has deepened, the proportion of service trade in international trade has been gradually increasing. By opening up the service market, enterprises can provide a wider range of services, such as finance, transportation, education, tourism, etc. The growth of the service industry creates more employment opportunities and economic growth points for countries (Du and Liu, 2023).

As a globally populous country and the second largest economy, China's bilateral trade with RCEP members can expand the market size of these nations. China's vast consumer market and demand potential provide more development and export opportunities for enterprises in RCEP countries. Through bilateral trade with China, RCEP countries can benefit from China's technology and management experience. China has advanced technology and manufacturing capabilities in many fields, and trade with China can promote technology transfer and cooperation, raising the industrial level and innovation capabilities of RCEP countries. In addition, China offers more investment opportunities for RCEP countries via bilateral trade (Jiang and Yu, 2021). China is one of the world's largest sources of foreign direct investment, and trade with China can attract more foreign investment, boost the scale and production of enterprises in RCEP countries, and thus create jobs. According to the resource allocation theory, bilateral trade achieves optimal resource allocation. China meets its needs through imports, while RCEP countries utilize their resources and labor through exports. This optimization of resource allocation improves production efficiency and economic growth.

2.2 Bilateral trade, pollution and carbon reduction

There are two main theories about the relationship between trade openness and pollution and carbon reduction. One is the theory of trade benefits, which means that trade openness is beneficial for reducing environmental pollution and carbon emissions. Existing research also strongly supports this viewpoint. As Frankel and Rose (2005) argued, trade helps propel economic growth, and trade is negatively correlated with air pollution. Kim et al. (2019) found that trade openness has a significant inhibitory effect on carbon emissions in developed countries, as developed countries typically tend to develop high value-added and low intensity service, as well as knowledge intensive industries, while outsourcing high energy and carbon emission industries to developing countries. Cai et al. (2022) believed that trade liberalization encourages domestic trading enterprises to choose more proactive pollution reduction strategies, that is, signing the CAFTA helps reduce the pollution emissions of trading enterprises. Tan and Sheng (2022) used Chinese enterprise data to study that export trade significantly suppressed corporate pollution emissions. Some scholars have examined the influencing factors of sustainable development and environmental protection from the perspective of green trade.

Olasehinde-Williams and Folorunsho (2023) tested the validity of Porter's Hypothesis by examining the combined impact of green trade and tightened environmental policies on the sustainable development of the European Economic Area. Lee et al. (2023) found that both green trade and economic complexity have made positive contributions to environmental protection in 24 EU countries, and their interaction has reinforced their individual benefits. This indicates that promoting both green trade and economic complexity can effectively promote sustainable development, encouraging countries to increase local production capacity or utilize international green trade.

The other is the trade-harming theory, which means that trade openness will worsen environmental quality and increase carbon emissions. Its representative theories mainly include the "pollution

paradise" hypothesis and the "race to the bottom line" hypothesis (Walter and Ugelow, 1979; Esty and Dua, 1997). Copeland and Taylor (1997) pointed out that free trade may lead to a negative cycle of low real income and environmental quality, and high pollution emissions. Li and Qi (2011) believed that trade openness has increased China's carbon emissions, and the environmental benefits of trade are smaller than the "race to the bottom line" influence. Wang and Xu (2015) found through their study of quarterly data in China that trade openness significantly encourages carbon emissions in the long term, meeting the "pollution paradise" hypothesis. Dai (2017) used the instrumental variables estimation method and found that trade openness will worsen environmental quality, of which export trade is the main reason for the deterioration of environmental. Khan et al. (2021) employed empirical evidence from the top ten manufacturing countries to show that commodity trade is positively related to economic growth and negatively related to environmental quality.

Bilateral trade between China and RCEP members could have an impact on the environmental quality and carbon emissions of RCEP countries through the following channels. Firstly, China has rich experience and advanced technology in clean energy, environmental protection technology, and sustainable development (Yu and Tsai, 2018). Through bilateral trade with China, RCEP countries can benefit from the spillover of Chinese technology, introduce and apply advanced environmental protection technologies, and thus facilitate the process of pollution and carbon reduction. Secondly, bilateral trade between China and RCEP countries can incentivize enterprises to adopt more environmentally friendly production methods and supply chain management, promoting the reduction of pollution and carbon emissions. Thirdly, China is one of the largest sources of foreign direct investment in the world. RCEP countries can attract more foreign investment and advance green development, pollution and carbon reduction projects and industries through bilateral trade with China.

As mentioned above, scholars have conducted extensive research on the relationship between trade openness, economic growth, as well as pollution and carbon reduction from different perspectives. Reviewing the existing literature, it is found that current research has mainly focused on the impact of trade openness on China's economic growth or environmental quality, while there is relatively little research has been done on the impact of bilateral trade with China on the economic growth or pollution and carbon reduction of other nations. Therefore, based on the Panel data of RCEP countries, this paper uses a combination of theoretical and empirical methods to evaluate the synergistic effect of "pollution and carbon reduction" and "economic growth" of bilateral trade.

3 Methodology and data

3.1 Model settings

In order to test the impact of bilateral trade between China and RCEP countries on economic growth and pollution and carbon reduction, a multivariate linear regression model is constructed in this paper. The balanced panel data for the RCEP countries from 1997 to 2020 is selected. The model is set up as shown in Equation 1:

$$y_{it} = \alpha_0 + \alpha_1 ctra_{it} + \sum_{j}^{T} \alpha_{j=2} control_{it}^{j} + \gamma_i + \delta_t + \varepsilon_{it} \quad (1)$$

where i and t represent country and year, respectively, y_{it} is the dependent variable of this paper, including economic growth ($pgdp_{it}$), environmental quality ($pm2.5_{it}$), and carbon emissions (pco_{it}), $ctra_{it}$ conveys the bilateral trade between China and RCEP countries, which is the core explanatory variable, $control_{it}^{j}$ is a set of control variables, including urbanization (urb_{it}), population density (pde_{it}), foreign investment openness (fdi_{it}), natural resource endowment (res_{it}), and government governance level (wgi_{it}), γ_i and δ_t represent national fixed effects and time fixed effects, respectively, ε_{it} is the random error term.

3.2 Variables

3.2.1 Dependent variables

The dependent variables include economic growth ($pgdp$), environmental quality ($pm2.5$) and carbon emissions (pco).

We adopt real *per capita* GDP as the proxy variable for economic growth, which is the most direct and widely accepted indicator to measure the level of economic development in a country or region (Zhang and Wang, 2023). The growth of *per capita* GDP reflects the overall scale of economic activity and the average living standard of residents, which is crucial for understanding how trade promotes or hinders economic growth.

PM2.5 concentration is chosen as the measure of environmental quality due to its status as a primary component of air pollution that directly affects human health and environmental quality (Sahoo and Sethi, 2022). With the acceleration of industrialization and urbanization, PM2.5 pollution has become a global environmental concern, and its level changes can intuitively reflect the potential impact of trade activities on environmental quality.

Per capita carbon dioxide emissions serve as the proxy variable for carbon emissions, reflecting energy consumption and greenhouse gas emissions in economic activities (Liu et al., 2023). Trade activities often accompany the cross-border flow of goods and services, significantly impacting carbon emissions. Therefore, including carbon emissions in our study is essential for understanding the relationship between trade and climate change.

3.2.2 Core explanatory variable

The core explanatory variable is bilateral trade ($ctra$), with 1997 as the base period and the actual trade volume between China and RCEP members as the proxy variable for bilateral trade. Bilateral trade is chosen as the core explanatory variable because it is a crucial driver of economic interactions between nations (Wang and Tao, 2024). Given the focus of our study on China and RCEP countries, the volume of trade between these partners provides a direct measure of economic engagement. Changes in bilateral trade can significantly impact the economic growth prospects, environmental pressures, and carbon emissions of both parties.

3.2.3 Control variables

The control variables include several items. This paper draws on the research of Wang Q. et al. (2018), Khan et al. (2019), Hamid et al.

(2022), as well as Li and Zhang (2023), and selects the following indicators that will simultaneously affect economic growth, environmental quality, and carbon emissions as the control variables.

Urbanization (*urb*): The proportion of urban population to total population captures the process of urbanization, which is known to drive both economic growth and environmental changes. Rapid urbanization often leads to increased industrialization, consumption patterns, and resource use, all of which can affect both economic prosperity and environmental degradation. Therefore, urbanization is an essential control variable to account for its confounding effects.

Population Density (*pde*): Population density measures the distribution of people across a given area. High population density areas tend to experience greater environmental pressures due to increased demand for resources and services. At the same time, these areas also often exhibit higher levels of economic activity and potential for technological advancements that can mitigate environmental impacts. Including population density as a control variable ensures that the estimated effects of bilateral trade are not merely reflecting differences in population distribution.

Foreign Investment Openness (*fdi*): The proportion of actual utilization of foreign investment to GDP reflects a country's openness to and integration with the global economy. There is a notable relationship between a country's participation in global value chains and its carbon emissions (Olasehinde-Williams and Özkan, 2023). Meanwhile, FDI, as a vital means for multinational corporations to organize global production networks, contributes to enhancing the host country's participation in global value chains (Zhao et al., 2023). FDI can bring in capital, technology, and knowledge that contribute to economic growth but may also lead to the transfer of polluting industries, thereby affecting environmental quality and carbon emissions. Controlling for FDI is crucial to disentangle its potential confounding effects from those of bilateral trade.

Resource Endowment (*res*): Measured by the proportion of total natural resource rent to GDP, resource endowment captures a country's abundance of natural resources (Xiong and Wang, 2018). Resource-rich countries often rely heavily on resource extraction for economic growth, which can have adverse effects on the environment and lead to the so-called "resource curse." Including resource endowment as a control variable helps isolate the unique impact of bilateral trade on economic growth and environmental outcomes, net of the effects stemming from a country's natural resource base.

Government Governance (*wgi*): The World Governance Indicators (WGI) offer a comprehensive assessment of a country's governance quality across six dimensions: political stability, corruption control, government effectiveness, regulatory quality, rule of law, and voice and accountability. Effective governance is essential for sustainable economic growth and environmental protection. By averaging these six sub-indicators, we capture the overall level of government governance, which is crucial in shaping policies and institutions that influence economic outcomes and environmental behaviors (Yuan et al., 2018). Controlling for governance quality is essential to isolate the impact of bilateral trade from that of the broader institutional and political environment.

TABLE 1 Descriptive statistics.

Variables	Obs	Mean	Std. Dev	Min	Max
pgdp	336	7.935	2.197	3.743	10.967
pm2.5	336	21.797	10.258	5.903	44.056
pco	336	6.048	5.574	0.150	19.500
ctra	336	13.287	2.488	6.626	17.507
urb	336	3.956	0.517	2.894	4.605
pde	336	4.749	1.743	0.880	8.993
fdi	336	0.913	1.226	−4.742	3.471
res	336	0.083	2.988	−8.693	3.563
wgi	336	0.226	1.012	−1.752	1.865

3.3 Data and descriptive statistics

This article focuses on 14 RCEP members over the period 1997 to 2020. Per capita carbon dioxide emissions data were collected from the IEA database, bilateral trade data between China and other countries were sourced from the China Statistical Yearbook, government governance data were sourced from the WGI database, and other variable data were collected from the World Bank's WDI database. Individual missing data shall be filled with Linear interpolation method. The descriptive statistics of variables are shown in Table 1.

4 Results and discussion

4.1 Benchmark regression

This paper employs the stepwise law of return method to examine the impact of bilateral trade on economic growth, environmental quality and carbon emissions of RCEP countries. Drawing on the approach of Fang (2023), in order to control for the effects of factors that do not change over time, we adopt a bidirectional fixed effect model for regression. Columns (1), (3), and (5) of Table 2 show the results without the addition of control variables, while columns (2), (4), and (6) show the results with the addition of control variables. The results of columns (1)–(2) indicate that bilateral trade significantly promotes the economic development of RCEP countries. The results of columns (3)–(4) convey that the coefficient of bilateral trade is significantly negative, meaning that bilateral trade has suppressed the deterioration of environmental quality in RCEP countries. The results of columns (5)–(6) imply that the coefficient of bilateral trade is positive, but it did not pass the 10% significance level test, showing that the influence of bilateral trade on carbon emissions in RCEP countries is not significant. Based on the above results, although bilateral trade has stimulated the economic development of RCEP countries and suppressed their environmental quality deterioration, it has not had a significant impact on carbon emissions. This indicates that bilateral trade has played a synergistic effect of "pollution reduction" and "economic growth", and there is still uncertainty about the "carbon reduction" effect.

TABLE 2 Benchmark results.

Variables	*pgdp*		*pm2.5*		*pco*	
	(1)	(2)	(3)	(4)	(5)	(6)
ctra	0.229***	0.262***	−0.473***	−0.706***	0.173	0.218
	(9.40)	(10.76)	(-3.06)	(-4.50)	(1.26)	(1.59)
urb		−0.558***		−2.009**		3.797***
		(-4.09)		(-2.28)		(4.95)
pde		−0.915***		7.046***		−2.129
		(-3.61)		(4.32)		(-1.49)
fdi		0.036***		0.159*		−0.157**
		(2.74)		(1.89)		(-2.13)
res		−0.143***		0.239		−0.312**
		(-5.75)		(1.49)		(-2.23)
wgi		−0.059		−0.902**		1.032***
		(-0.89)		(-2.09)		(2.74)
Constant	5.285***	11.211***	27.786***	5.922	3.665**	−1.738
	(17.99)	(8.46)	(14.85)	(0.69)	(2.21)	(-0.23)
Country effect	Yes	Yes	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.7083	0.7499	0.7062	0.7421	0.1138	0.2490
N	336	336	336	336	336	336

Note: ****, **, *respectively indicate significant at the 1%, 5%, and 10% levels, and the values in () are the corresponding t-statistic.

TABLE 3 Robustness results.

Variables	GDP	Ecological footprint	Carbon footprint
	(1)	(2)	(3)
ctra	0.257***	−0.176*	−0.032
	(10.50)	(-1.96)	(-0.58)
Control variables	Yes	Yes	Yes
Country effect	Yes	Yes	Yes
Time effect	Yes	Yes	Yes
R^2	0.8341	0.2461	0.1921
N	336	336	336

Note: ****, **, *respectively indicate significant at the 1%, 5%, and 10% levels, and the values in () are the corresponding t-statistic.

4.2 Robust test

To examine the reliability and robustness of the benchmark results mentioned above, this paper reconducts empirical estimation from the perspective of replacing the dependent variable. First, referring to the method of Huang et al. (2022), real GDP was used to characterize economic development. The results are shown in column (1) of Table 3. It can be found that the coefficient of bilateral trade on the economic development of RCEP countries is still significantly positive, conveying that the conclusion that bilateral trade can enhance the economic development of RCEP countries is robust. Then, drawing on the research of Aydin et al. (2019), ecological footprint can better measure the sustainability of the ecological environment. Therefore, we use ecological footprint as the proxy variable of environmental quality (Wang and Dong, 2019; Sui and Chen, 2021). The results are shown in column (2) of Table 3. Bilateral trade has substantially curbed the expansion of ecological footprints,

TABLE 4 Heterogeneity test results.

Variables	ASEAN countries			Non-ASEAN countries		
	pgdp	*pm2.5*	*pco*	*pgdp*	*pm2.5*	*pco*
	(1)	(2)	(3)	(4)	(5)	(6)
ctra	0.241***	−0.634***	0.197	0.237**	1.769**	−0.334
	(8.42)	(-3.51)	(1.37)	(2.25)	(2.62)	(-0.45)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Country effect	Yes	Yes	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.7402	0.7632	0.3163	0.9175	0.8739	0.7140
N	240	240	240	96	96	96

Note: ****, **, *respectively indicate significant at the 1%, 5%, and 10% levels, and the values in () are the corresponding t-statistic.

implying that bilateral trade is robust in curbing the deterioration of environmental quality. Finally, according to the research of Sun and Shen (2016), the carbon footprint index is employed to represent carbon emissions. The calculation of the carbon footprint is conducive to formulating targeted emission reduction strategies (Fenner et al., 2018). The results of column (3) in Table 3 show that the coefficient of bilateral trade is not significant, indicating that bilateral trade has no considerable influence on the carbon footprint of RCEP countries, which supports the robustness of the above benchmark results.

4.3 Heterogeneity test

The above empirical results suggest that, overall, bilateral trade significantly boosts economic growth and dampens environmental quality deterioration in RCEP countries, but does not play a role in reducing carbon emissions. Are there, then, differences in this result between different types of countries? To answer this question, this paper will examine the heterogeneous impact of bilateral trade on "pollution and carbon reduction" and "economic growth" from the perspective of location characteristics. The RCEP membership is made up of 15 countries, including China, Japan, South Korea, New Zealand, Australia and ten ASEAN countries. Given that this article focuses on bilateral trade between China and RCEP countries, the total sample is divided into ASEAN countries (10 countries) and non-ASEAN countries (4 countries) based on location and economic characteristics. Of these, all the countries in the ASEAN group, except Singapore, are developing countries, while the samples in the non-ASEAN group are developed countries.

Table 4 columns (1)–(3) report the estimated results of the ASEAN group of countries, while columns (4)–(6) state the results of the non-ASEAN group of countries. By comparing the coefficients of bilateral trade in columns (1) and (4), it was found that bilateral trade has a considerable positive effect on economic growth in both ASEAN and non-ASEAN nations. Bilateral trade has a greater economic growth effect in ASEAN countries compared to non-ASEAN countries. The possible reason is that ASEAN countries are still in the development stage in some industrial fields and have a high demand for technology and knowledge. As a leading country in manufacturing and technological innovation, China possesses advanced technology and professional knowledge. Through bilateral trade, China can transfer technology and knowledge to ASEAN countries, facilitating their industrial upgrading and economic development. In addition, there are certain similarities in cultural backgrounds and business habits between China and ASEAN countries, which helps both parties to establish and develop business cooperation relationships more easily (Ruan et al., 2022). The results of columns (2) and (5) reflect that bilateral trade has improved the environmental quality of ASEAN countries, while deteriorating the environmental quality of non-ASEAN countries. The explanation given in this article is that through trade cooperation with ASEAN countries, China can spread environmental protection technologies to ASEAN countries, helping them increase environmental quality. In addition, Chinese enterprises can also introduce advanced environmental protection equipment and technology into ASEAN countries to optimize their environmental governance level (Wang and Gao, 2019). Compared with developed countries, China's environmental standards may be relatively low. If Chinese products cause more pollution to the environment during the production process, which leads to a deterioration of the environmental quality in developed countries. From the results of columns (3) and (6), it was found that the coefficients of bilateral trade did not pass the 10% significance level, indicating that bilateral trade did not have carbon reduction effects in both ASEAN and non-ASEAN groups.

4.4 Mechanism verification

The previous analysis shows that although bilateral trade has advanced economic growth and environmental quality in RCEP countries, it has no obvious impact on local carbon emissions. Considering that bilateral trade may reduce regional carbon emissions by technological innovation and encourage the level of information infrastructure, it may also increase regional carbon emissions by supporting industrialization. This paper aims to identify and examine these two pathways of action. Referring to

TABLE 5 Mechanism verification results.

Variables	Technological innovation	Information infrastructure	Industrialization
	(1)	(2)	(3)
ctra	0.154***	9.136***	2.144***
	(3.25)	(6.37)	(3.20)
Control variables	Yes	Yes	Yes
Country effect	Yes	Yes	Yes
Time effect	Yes	Yes	Yes
R^2	0.5995	0.8514	0.1624
N	336	336	336

Note: ****, **, *respectively indicate significant at the 1%, 5%, and 10% levels, and the values in () are the corresponding t-statistic.

the practices of Jiang and Luo (2022) and Zhang et al. (2023), Equation 2 is constructed for mechanism validation:

$$z_{it} = \beta_0 + \beta_1 ctra_{it} + \sum_{j}^{T} \beta_{j=2} control_{it}^{j} + \gamma_i + \delta_t + \varepsilon_{it} \quad (2)$$

where z_{it} is a mechanism variable, which is used to examine the relationship between mechanism and core explanatory variables, including technological innovation, information infrastructure and industrialization level. And separately adopt the number of patent applications, internet penetration rate, and industrial value added/GDP as proxy variables for the above three. According to the existing literature, if β_1 is significant and the sign is positive, information infrastructure will restrain carbon emissions (Chen et al., 2023; Xie et al., 2023), and industrial development boost carbon emissions (Wang S. et al., 2018), it indicates that bilateral trade can affect carbon emissions of RCEP countries via z_{it}, but the direction of its impact is uncertain.

Table 5 reports the results of mechanism testing. It is not difficult to find that bilateral trade suppresses carbon emissions by stimulating technological innovation and information infrastructure in RCEP countries, while bilateral trade encourages carbon emissions via supporting industrialization in RCEP countries. Based on the analysis of the two opposite pathways mentioned above, it is once again evident that the "carbon reduction" effect of bilateral trade on RCEP countries is not significant.

4.5 Further discussion

4.5.1 Preliminary preparation of PVAR model

With the aim of studying the dynamic interaction among bilateral trade, economic growth and environmental quality, this paper constructs a panel vector autoregression (PVAR) for analysis. The PVAR model does not require presetting causal relationships between variables and distinguishing between endogenous and exogenous. Instead, all variables are treated as endogenous variables, and the interaction between each variable and the lagged term is analyzed. The model is set up as follows in Equation 3:

TABLE 6 Root of unity test results.

Test	$ctra_{it}$		*pgdp*		*pm*2.5	
	I (0)	I (1)	I (0)	I (1)	I (0)	I (1)
LLC	−0.51	−9.80***	−0.47	−9.19***	1.41	−7.41***
IPS	−0.47	−8.29***	−3.87***	−9.28***	1.89	−9.26***
HT	−2.57***	−21.48***	−6.69***	−20.73***	−0.26	−30.13***
ADF	34.89	202.90***	47.57**	197.68***	9.09	153.51***

Note: ****, **, *respectively indicate significant at the 1%, 5%, and 10% levels.

$$Y_{it} = \alpha_0 + \sum_{j=1}^{k} \alpha_j Y_{i,t-j} + \beta_i + \gamma_t + \quad (3)$$

where Y_{it} is a column vector that includes bilateral trade, economic growth, and environmental quality, α_j represents the coefficient matrix of the lagging variable, β_i is the country effect column vector, reflecting individual differences in cities, γ_t represents a dummy variable of time effect, reflecting the impact of time changes on different cities, ε_{it} is a random perturbation term.

To ensure the accuracy of model estimation and avoid the phenomenon of "pseudo regression", we conducted stationarity tests on three variables: bilateral trade, economic growth, and environmental quality. Referring to the research of Wang and Xiang (2022), this paper selects LLC test, IPS test, HT test and ADF test to investigate whether there is a Root of unity in variables. See Table 6 for the results. It can be seen that bilateral trade, economic growth, and environmental quality cannot be completely significant at the 10% level, conveying that all three variables are unstable. However, after first-order difference processing, all variables passed the 1% significance test, indicating that bilateral trade, economic growth, and environmental quality are in a first-order single integer sequence. In order to further test whether there is a long-term stable equilibrium relationship among the three variables, this article employs the Kao test to conduct cointegration tests on the data after the first-order difference of all variables. The Kao test results reply that the t-statistic value

TABLE 7 Selection of optimal lag order.

Lag order	CD	J	J *p*-value	MBIC	MAIC	MQIC
1	0.999	49.559	0.005	−101.195[a]	−4.441	−43.311[a]
2	0.999	30.787	0.030	−69.716	−5.213[a]	−31.127
3	0.999	15.336	0.082	−34.915	−2.664	−15.621

Note: [a]represents the optimal lag order selected based on MBIC, MAIC, and MHQIC, criteria.

TABLE 8 GMM estimation results of PVAR model.

Variables	h_Dctra	h_Dpgdp	h_D pm2.5
L.h_Dctra	0.943***	0.221***	−0.080***
	(22.50)	(6.07)	(-3.52)
L.h_Dpgdp	0.067	0.202	0.089
	(0.48)	(1.15)	(0.79)
L.h_Dpm2.5	0.012	−0.037*	1.122***
	(1.02)	(-1.85)	(29.68)

Note: ***, **, *respectively indicate significant at the 1%, 5%, and 10% levels. The data in () is the z-statistic.

of ADF is −10.832, and the P-value is 0.000, which rejects the original hypothesis, meaning a stable equilibrium relationship between bilateral trade, economic growth, and environmental quality.

Before conducting PVAR model estimation, it is necessary to determine the optimal lag order of the model. Drawing on the approach of Yan and Wu (2016), this article uses MBIC, MAIC, and MQIC to determine the lag order. According to the results in Table 7, the first order PVAR model has the smallest MBIC and MQIC, while the second order PVAR model has the smallest MAIC. Therefore, the lag order of the PVAR model is determined to be 1 through comprehensive evaluation.

4.5.2 GMM estimation results

After determining the root of unity test and the optimal lag order, this paper studies the relationship between bilateral trade, economic growth and environmental quality based on generalized method of moments (GMM). GMM estimation is a parameter estimation technique used to estimate the parameters within a PVAR model. The GMM estimation method for PVAR models enables the precise estimation of autoregressive coefficients, cross-correlation coefficients, and their corresponding confidence intervals for each variable, thereby uncovering the immediate and long-term dynamic relationships among variables. Furthermore, it captures the long-run equilibrium trends of the model, providing a solid foundation for forecasting the future states of variables. Additionally, the models constructed using this estimation method serve as potent instruments for economic simulations and policy impact analyses. Table 8 reports the estimated results of GMM. The results show that bilateral trade with a lag of one order has a substantial boosting effect on its current level, implying that the increase in bilateral trade has a certain inertia. When economic growth is taken as the dependent variable, lagged first-order bilateral trade has a considerable positive influence on current economic growth. However, the higher the PM2.5 value of lagged first-order, the less conducive it is to economic growth, indicating that the improvement of lagged first-order environmental quality is conducive to increasing the current economy. The development of environmental protection industries can create more job opportunities (Panwar et al., 2011). For example, developing renewable energy, clean technology, and environmental monitoring, so as to attract a large number of highly skilled and value-added employment opportunities and propel economic growth. When PM2.5 is used as the dependent variable, the coefficient of lagged first-order bilateral trade is significantly negative, indicating that the previous period's bilateral trade improved the current environmental quality. The lagging first-order PM2.5 has a considerable promoting effect on the current PM2.5, indicating that the optimization of environmental quality has a sustained characteristic. Environmental problems are often the result of long-term accumulation and impact. Only through continuous environmental protection measures, monitoring, and management can we achieve continuous improvement of environmental quality and sustainable development.

4.5.3 Impulse response analysis

To visually display the response mechanism between bilateral trade, economic growth, and environmental quality, we adopt pulse response graphs for analysis. The impulse response approach is to characterize the current and future dynamic response of a standardized shock on the error term of one variable against another, while keeping the other variables under control. The pulse response function is shown in Figure 1. It can be observed that all impulse response plots exhibit a convergence trend, indicating that the model has stability.

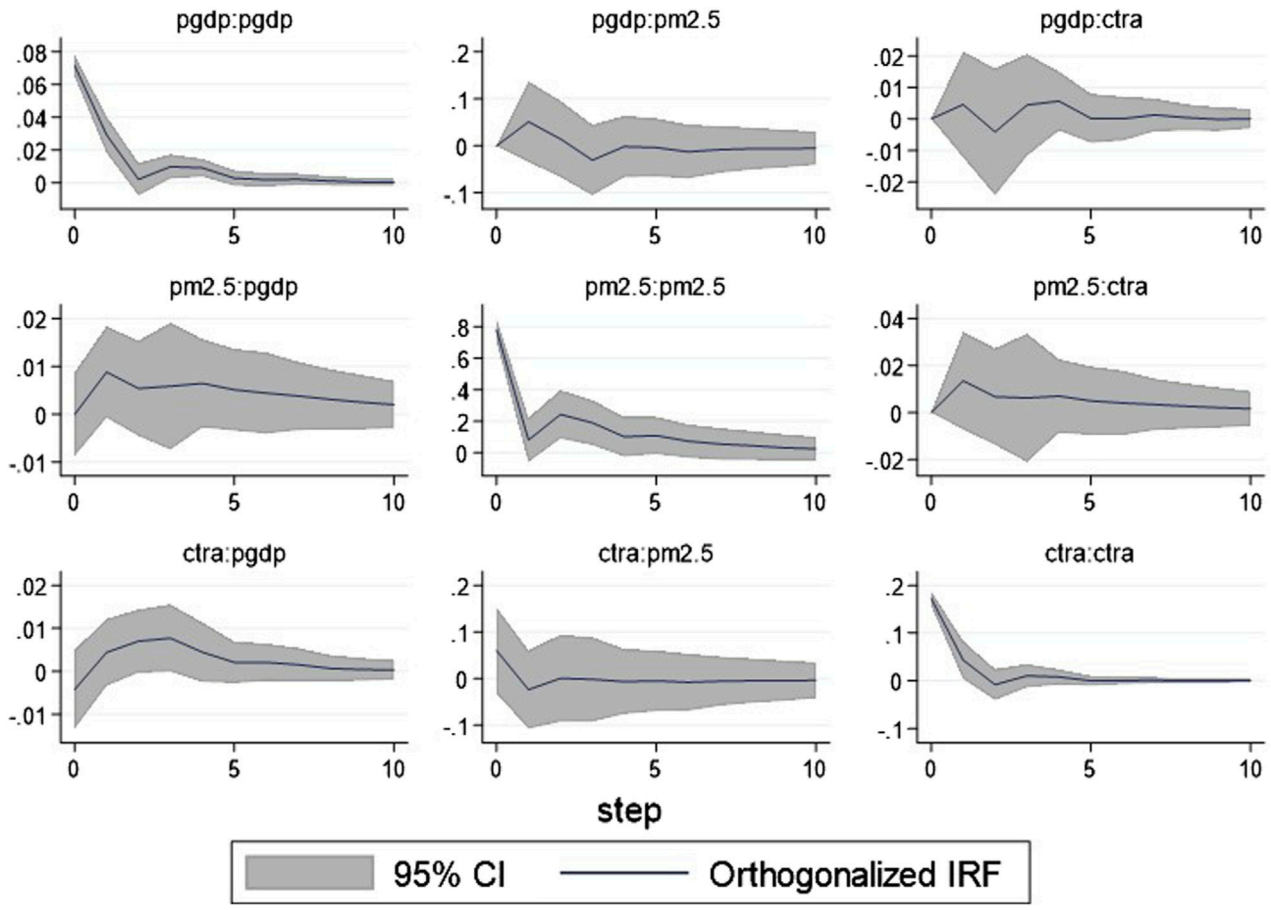


FIGURE 1
Pulse response diagram.

When economic growth is affected by one standard deviation, it can exhibit an obvious positive impact on itself, followed by a rapid decline. In the third period, there is a weak fluctuation around the zero axis, until the influence on itself approaches zero in the fifth period. After being impacted by the standardization of economic growth, PM2.5 experienced a strong positive reaction in the first phase, with the reaction intensity reaching its maximum. Later, it drops to the third phase and becomes a negative response, fluctuating around the null axis. In the sixth phase, the effect largely disappears, meaning that economic growth initially causes environmental deterioration, and over time, economic growth improves environmental quality. Bilateral trade showed a weak positive response when affected by economic growth, then decreased to a negative response in the second period, and rapidly increased to a positive response in the third period, until the impact in the fifth period basically disappeared, which implies that economic growth has a sustained effect on environmental quality and bilateral trade in the long run.

When PM2.5 is influenced by a standard deviation, it promptly exhibits a strong positive effect on itself, with the impact value reaching its maximum, and then rapidly decreasing to become negative. In the second phase, there is a small increase followed by a gradual decrease until it approaches 0 in the sixth phase. When economic growth and bilateral trade are affected by PM2.5, the reaction is mostly consistent. In the first phase, there is a positive reaction, and the reaction intensity reaches its maximum. It then decreases to the second phase and stabilizes, and gradually decreases to the null axis in the fourth phase. This denotes that improving environmental quality is not conducive to economic growth and bilateral trade in the initial stage, while over time, environmental quality will have a positive effect on both.

When bilateral trade is affected by a standard deviation, it speedily shows an obvious positive impact on itself, followed by a rapid decline. In the third period, it begins to fluctuate weakly around the null axis, until the effect on itself approaches zero in the fifth period. When economic growth is impacted by bilateral trade, it straightaway exhibits a negative response, and then rapidly increases to a positive influence in the first period. By the third period, the positive response reaches its maximum and begins to decline until the effects of the fifth period disappears. When PM2.5 is influenced by bilateral trade, it instantaneously shows a positive response, and then rapidly decreases to a negative impact in the first phase. In the second phase, it shows a slight increase and approaches zero, indicating that the influence of bilateral trade on environmental quality is relatively short-lived.

5 Conclusions and policy recommendations

5.1 Conclusions

The parallel pursuit of "pollution and carbon reduction" alongside "economic growth" not only aligns with sustainable development goals but also fosters green economic transformation, enhancing resource efficiency, innovation, and international competitiveness. Employing panel data from China and RCEP member countries, this study examines the intricate interplay between bilateral trade, economic growth, and environmental quality. The key conclusions are:

(1) Bilateral trade significantly boosts economic growth and environmental quality in RCEP nations, yet its impact on carbon emissions is nuanced. It curbs emissions through technological innovation and information infrastructure improvements but exacerbates them via industrialization. Thus, the net "carbon reduction" effect hinges on the balance of these competing forces.
(2) The effects of bilateral trade vary across RCEP regions. Trade with ASEAN nations more robustly drives economic growth, while environmental benefits are concentrated in ASEAN, with non-ASEAN countries experiencing deterioration. Both regions show minimal direct impact on carbon emissions from trade.
(3) The PVAR model reveals inertia in bilateral trade's growth-enhancing and environmental quality-improving effects. Lagged bilateral trade and environmental improvements positively influence current economic growth, underscoring the need for sustained efforts.
(4) Pulse response analysis indicates that initial economic growth can temporarily compromise environmental quality, but over time, it improves environmental outcomes. Conversely, while initial environmental gains may not immediately bolster trade or growth, they eventually do so. Bilateral trade's environmental impact is relatively short-lived, necessitating continuous attention.

5.2 Policy recommendations

Building on these findings, the following practical implications and recommendations aim to guide decision-making, managerial practices, and policy development in RCEP countries:

(1) Harmonized Environmental Standards. Recognizing the win-win potential of environmentally friendly trade, RCEP partners should establish uniform environmental standards and certification mechanisms. This includes promoting technologies that reduce pollution, enhance energy efficiency, and foster circular economies. Strengthening environmental information sharing and communication will facilitate joint efforts to tackle environmental challenges and ensure trade aligns with sustainability goals.
(2) Technological Cooperation and Digital Transformation. China and RCEP countries should collaborate on technological innovation, particularly in low-carbon and environmentally friendly technologies. Policy incentives such as financial support, intellectual property protection, and tax benefits can spur R&D cooperation. Digitalization and internet infrastructure upgrades can improve efficiency, reduce emissions, and support sustainable trade practices. Establishing rigorous carbon management systems, including emission standards and monitoring, is crucial to mitigating industrialization's carbon footprint.
(3) Tailored Cooperation Strategies. Given regional heterogeneity, China and ASEAN should deepen trade ties beyond traditional sectors, focusing on high-value environmental technologies, green agriculture, and renewable energy. China can offer environmental technology assistance, transfers, training, and financial support to ASEAN, fostering bilateral cooperation and addressing shared environmental challenges. Encouraging corporate social responsibility projects in ASEAN will further strengthen sustainable trade ties.

Some study limitations must be considered when interpreting our findings. Firstly, while we have initially explored the varied impacts of bilateral trade on economic growth and environmental pollution in different regions within RCEP countries (such as ASEAN and non-ASEAN countries), this analysis has not delved into more specific country-level or industry-level details. Secondly, in examining the potential mechanisms behind why bilateral trade has not effectively reduced carbon emissions, we have utilized a mechanism test encompassing two pathways, but there may still be other complex factors or pathways that have been overlooked. In our future research, we will firstly refine our analysis further to delve into the specific impacts of bilateral trade on economic growth and environmental pollution across different countries and industries, as well as the underlying reasons behind these impacts. Secondly, we will introduce additional variables and pathways, such as technology spillover effects, the intensity of environmental regulations, and changes in consumer preferences, to more comprehensively reveal the complex mechanisms through which bilateral trade affects carbon emissions reduction.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YW: Conceptualization, Methodology, Project administration, Resources, Writing–review and editing. RS: Software, Supervision, Writing–review and editing. CG: Conceptualization, Data curation, Methodology, Software, Writing–original draft. SY: Funding acquisition, Resources, Visualization, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The impact of pilot policies for low carbon city construction on the development of urban circular economy multiple time-point difference-in-differences model

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Introduction: As a means of environmental regulation, the low-carbon city pilot policy aims to address climate change and alleviate environmental resource pressures in economic development. The development of low-carbon cities often requires changes to the existing industrial and energy structures, which will have a significant impact on the regional economy.

Methods: The study is based on panel data from 273 prefecture level cities in China from 2012 to 2022, and uses the Analytic Hierarchy Process and Entropy Comprehensive Evaluation Method to construct an evaluation index system for urban circular benefits. Finally, the multiple time point differences model and mediation effect model were used to evaluate the impact and influencing factors of policies on urban economy.

Results: The results indicate that at the 1% level, the explanatory variable coefficient significantly improves the level of urban circular economy development after adding control variables. The construction of low-carbon pilot cities has improved the performance of circular economy development by about 6.42%. The mediating effect of industrial structure rationalization is significantly positive at the 1% significance level, indicating that the construction of low-carbon pilot cities has greatly promoted the coordinated development of industrial relations within China's low-carbon development regions.

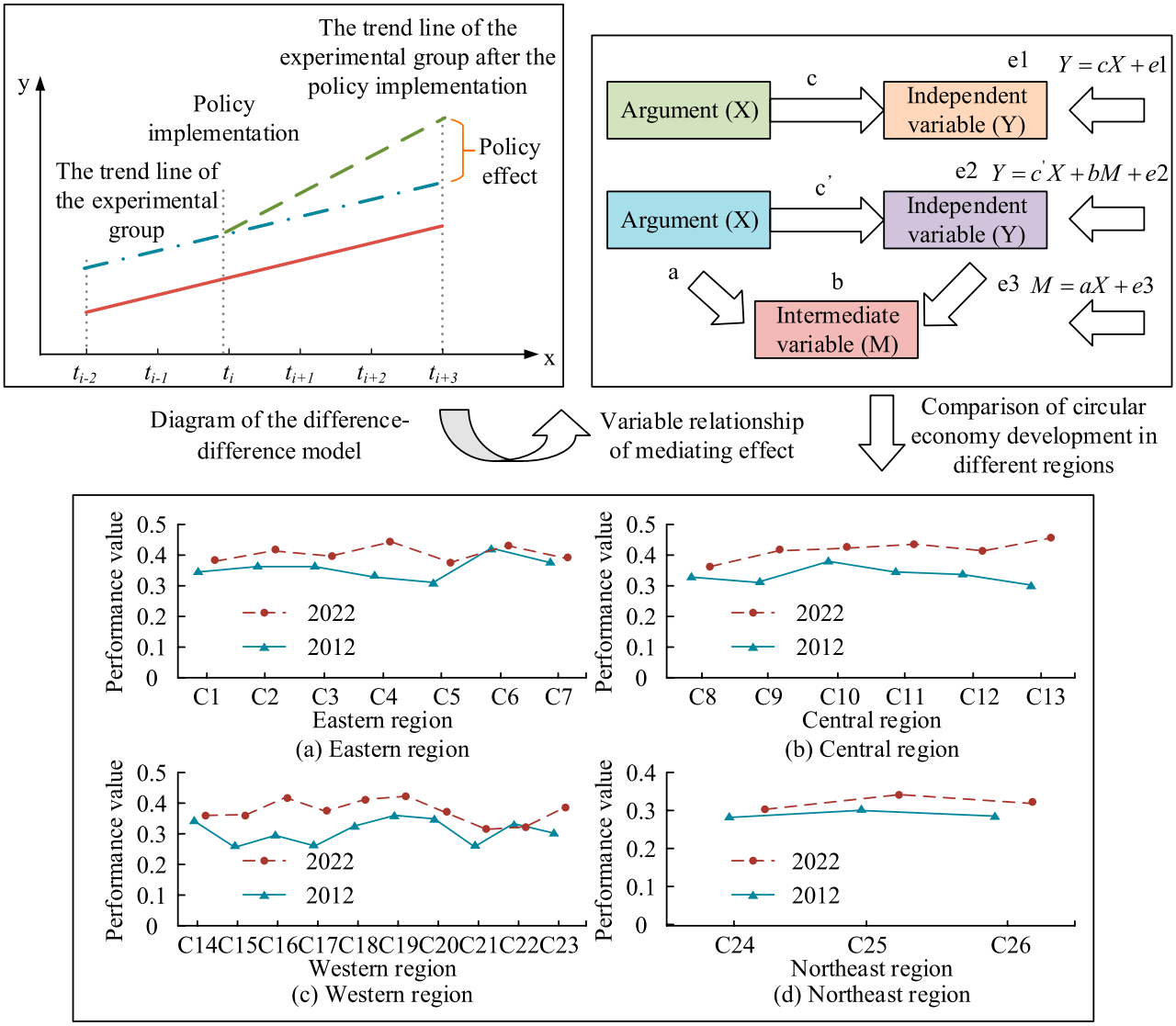
Discussion: It can be seen that the low-carbon city pilot policy has a significant promoting effect on China's economic development and the development of urban circular economy. Therefore, it is recommended to further expand the pilot scope of low-carbon cities and fully leverage their promoting role.

KEYWORDS

low-carbon, pilot policies, city, circular economy, PSM-DID

1 Introduction

Low-carbon city (LC) is an environmental regulation policy to address climate change, and it is of great significance for an environmentally friendly society (Chen et al., 2021). Against the backdrop of low-carbon economy (LE) strategies being implemented by national and local governments, LE is also an important development trend and core strategy for future economic and social development. Its core lies in the sustainable



GRAPHICAL ABSTRACT
This article is based on panel data from 273 prefecture level cities from 2012 to 2012, and uses a multi time difference model to analyze the impact of low-carbon city pilot policies on the development of urban circular economy. The research results indicate that the construction of low-carbon pilot cities has significantly promoted the coordinated development of intra regional industrial relationships.

utilization of ecological resources, and it aims to achieve green development by a low-pollution and low-energy consumption industrial development system (Liu et al., 2022a). In terms of low-carbon city construction and urban economic development, many domestic and foreign scholars, such as Chen et al. (2023a), have pointed out in their research that CSR can effectively stimulate green exploratory innovation through mandatory and market-driven regulation, but voluntary regulation has negative effects on it. Secondly, other studies have also proposed that circular economy practices can significantly improve enterprise performance, especially in state-owned, large and heavily polluting enterprises, while innovation and digital transformation strategies as well as moderate practice intensity are the key (Chen and Dagestani, 2023). Finally, relevant studies have pointed out that air quality monitoring policies significantly improve urban ecological efficiency, and governments and ngos play different roles in this process to achieve sustainable urban development (Chen et al., 2023b). In addition, the current policy implementation mechanism mainly focuses on urban LE and total factor productivity, and takes carbon emissions as an evaluation index. The research on circular economy mainly focuses on the connotation of circular economy and its impact on economic and social development. As the problem of climate change intensifies, research on the impact of low-carbon policies on economic development is helpful in finding a path of coordinated development between the economy and the environment while achieving carbon emission reduction. As a model of sustainable development, CE emphasizes efficient use of resources and environmental protection. Therefore, studying the impact of low-carbon policies on CE can help understand their role in resource recovery and reducing pollution emissions. This paper focuses on the effects of the LC on the development of the CE and explores their underlying mechanisms. It innovatively constructs a novel system

for urban CE development and comprehensively measures the development level of prefecture-level cities using the analytic hierarchy process (AHP) and entropy weight method. A multiple time-point difference-in-differences (DID) model is built to assess LC construction's impact on urban CE. The main innovations of this study are as follows: Firstly, an index system is constructed to evaluate the development of urban CE. This is achieved by utilizing AHP and entropy methods to comprehensively measure 273 prefecture-level cities in China. This approach allows for a comprehensive and objective reflection of the development of urban CE. Secondly, the multiple time-point DID model is used to evaluate the impact of LC pilot policies on the development of CE as a quasi-natural experiment, which improves the accuracy of the model and reduces selection bias and endogenous problems. Furthermore, the mediation effect model is employed to elucidate the mechanism through which LC pilot policies influence the advancement of CE. The intermediary effects of industrial structure rationalization, green technology progress, energy consumption structure optimization, and upgrading are utilized to reveal the policy effect. Finally, based on the data from 273 prefecture-level cities from 2012 to 2022, a large sample empirical study is conducted to enhance the robustness and universality of the results, and the conclusions are more representative. The paper aims to provide scientific and effective decision support for accelerating China's CE system and achieving green transformation.

This study is divided into six parts. The first part introduces the background and importance of LC pilot projects, and elaborates on the concepts of LE and CE. The second part summarizes the research on the impact of urban CE both domestically and internationally. The third part introduces research methods, discusses environmental regulatory tools and their impact mechanisms on the CE, then designs performance indicators and measurement methods for the CE, and constructs a multiple time-point DID model and mediation effect model. The fourth part is empirical analysis, which includes an examination of the impact of policies on CE performance and a discussion of regional differences. Additionally, it addresses the indirect impact of policies on CE through industrial structure rationalization, green technology progress, and energy structure optimization. The fifth part proposes policy adjustment suggestions for regional differences, including green technology and energy structure optimization. The sixth part summarizes the research methods and experimental results, and proposes future research directions.

2 Related works

As the national and local governments gradually implements the development strategy for LE, the LE begins to receive attention from countries around the world. Many scholars have conducted research and evaluation on its implementation effects in various aspects. Firstly, Yu Y and other scholars conducted in-depth research on the correlation between LC and carbon emission efficiency, and used the DID combined with propensity score matching (PSM) to prove that the LC significantly improved carbon emission reduction in Central and Eastern Europe (Yu and Zhang, 2021). Liu F and other scholars evaluated the LC in China by incorporating carbon emissions into the evaluation framework. Based on a multi-period DID, they found that LC can achieve both direct carbon emission reduction and indirect reduction through optimizing industrial structure, technological innovation, and other means (Liu, 2022). Wen S and other scholars used panel data from 208 cities and calculated the impact of LC on carbon emission efficiency through PSM and DID. The study showed that the overall LC could significantly improve the carbon dioxide emission rate in pilot areas (Wen et al., 2022). In terms of environmental pollution control, Liu Z and other researchers took the LC in China to analyze the motivation of local sustainable development action under authoritarian background. The study demonstrated that LC facilitated the advancement of environmental governance, thereby fostering the sustainable development of local areas (Liu et al., 2022b). Yan J and other researchers constructed a PSM-DID and mediation effect model using panel data from 271 cities in China. Research results showed the average annual concentration of PM2.5 decreased by 14.29% (Yan et al., 2021).

In terms of economic development, Qiu S and other scholars used the PSM-DID model to prove that in large cities, non-resource cities, and eastern cities, LC projects positively impacted regional economic development (Qiu et al., 2021). In the CE, Gong Z and other researchers based on the enterprise social responsibility research of radial basis function neural network, constructed a low-carbon CE system. The study verified the coupling development relationship between the environment and economy through examples, and clarified the connotation of low-carbon CE (Gong et al., 2021). Zhang W and other scholars used panel data from 30 provincial-level administrative regions to empirically study how carbon emissions trading promotes green technology innovation. The study found that at the current stage, carbon trading had a certain inhibitory impact on green technology innovation, but significantly reduced carbon emissions and carbon intensity (Zhang et al., 2022).

In conclusion, few studies have comprehensively analyzed economic development and CE. Many studies use provincial data and ignore differences at the prefecture-level. For example, Yan et al. (2021) used the PSM-DID model but did not delve into the situation of prefecture level cities. The traditional DID model was difficult to fully capture the dynamic effects and regional differences of policies when processing multi-time points and multi-region data. Gong et al. (2021) discussed the relationship between corporate social responsibility and low-carbon CE, but did not systematically analyze the mediating effect. To reduce the selection bias and improve the robustness of the results, the evaluation index system of urban CE development is constructed. Combining AHP and entropy to measure the development level of CE in prefecture-level cities, the PSM-DID model is adopted to consider the influence of policies in the time dimension.

3 Evaluation method of the effect of LC construction on the development of urban CE

To analyze the level of CE development in cities, this study uses panel data from 273 prefecture-level cities in China from 2012 to 2022, and establishes a corresponding evaluation system. Combined with the AHP and entropy weight methods, the level of CE

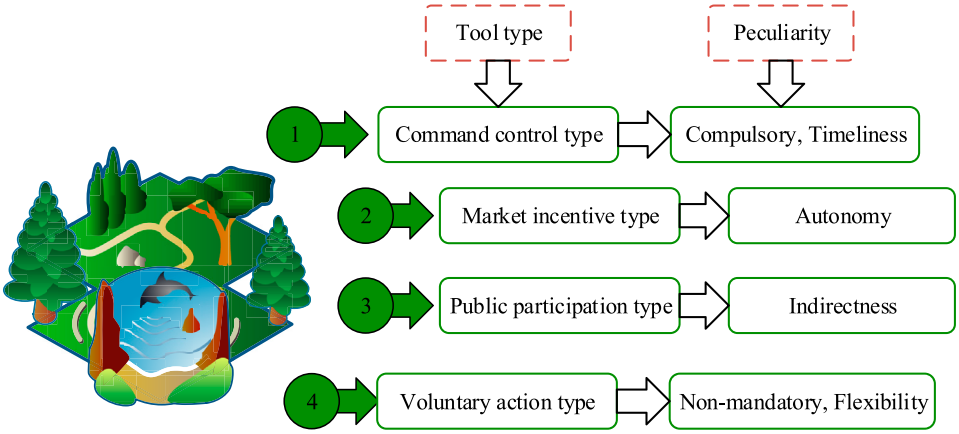


FIGURE 1
Types of environmental regulation tools.

development in each city is evaluated. Furthermore, a multiple time-point DID model is constructed to assess the impact of LC on urban CE. Finally, based on the mediating effects model, various factors' impact on CE development degree in cities is examined.

3.1 The promotion mechanism of LC on urban CE

Environmental regulation refers to the various regulatory measures taken by the government or authorities in handling environmental issues. Its purpose is to protect the environment, and use market mechanisms and public roles to directly or indirectly intervene and regulate enterprises that cause environmental pollution in the production environment. Based on the existing research on environmental regulation policies and the development theory of CE, environmental regulation tools can be divided into different types according to their functional mechanisms and characteristics, as shown in Figure 1 (Teymouri et al., 2022).

In Figure 1, there are four main types of environmental regulatory tools: command and control, market-based incentives, public participation, and voluntary actions. Command and control involve mandatory regulation of wastewater treatment plants at the government level using legal and administrative means. Corresponding laws and regulations should be formulated to unify emission standards and technological standards for pollutants. Market-based incentives adjust the costs and benefits of pollution-emitting units through various economic tools, establish systems such as emissions trading permits, impose pollution taxes, and provide compensatory subsidies. Public participation involves the public disclosure of environmental monitoring information and the signing of voluntary environmental agreements to facilitate public participation and reflect the demands and opinions of the masses through multiple channels. Voluntary actions refer to voluntary conservation activities initiated by residents, enterprises, and non-governmental organizations, as well as the establishment of nature reserves and the creation of eco-friendly cities. LCs are environmental regulatory measures proposed to address climate change. Their purpose is to promote cities' green and low-carbon transformation in various ways for environmentally friendly society construction (Liu et al., 2021; Song and Ouyang, 2020). Within pilot cities, the responsibility for carbon emission reduction has shifted from provincial to prefecture-level cities and county-level cities. However, limiting the scope of policy pilots to specific regions is conducive to formulating reasonable low-carbon development plans based on regional characteristics, accelerating policy implementation, and ensuring the effectiveness of policy execution. LE is not only the foundation of a country but also a guarantee for sustainable social development (Deng and Shangguan, 2021). CE is an economic development model based on ecological economics, with comprehensive utilization efficiency of resources as its core and sustainable development as its goal. Based on the principles of ecological economics and sustainable development, efficient use of resources is achieved by reducing resource waste and environmental damage. The specific structure and level of CE are shown in Figure 2 (Preethi and Mamatha, 2023).

In Figure 2, both LE and CE are essentially sustainable economic models and components of the green economy. "Low-carbon" refers to achieving carbon reduction in the production and living processes, while "LE" aims to improve comprehensive resource utilization. Building a LE system can promote green transformation in various aspects, such as production, circulation, and consumption, and it is an important way to promote carbon reduction and optimize energy utilization efficiency (Mahdiraji, 2021). On the other hand, building a CE system that targets resource conservation can adjust the city's energy consumption structure through adjustments in energy structure, control of energy consumption, reduction of coal consumption, and realization of low-carbon development. Under the background of high-quality development, the country's attention to the ecological environment is increasing, and building LC has become the main approach to addressing environmental pollution. The pilot policies for LC have both direct and indirect effects on CE. The management of solid waste pollution, energy consumption, and the green transformation of production methods are important issues that need to be resolved urgently in CE. The core issue is how to minimize the environmental impact in the production process.

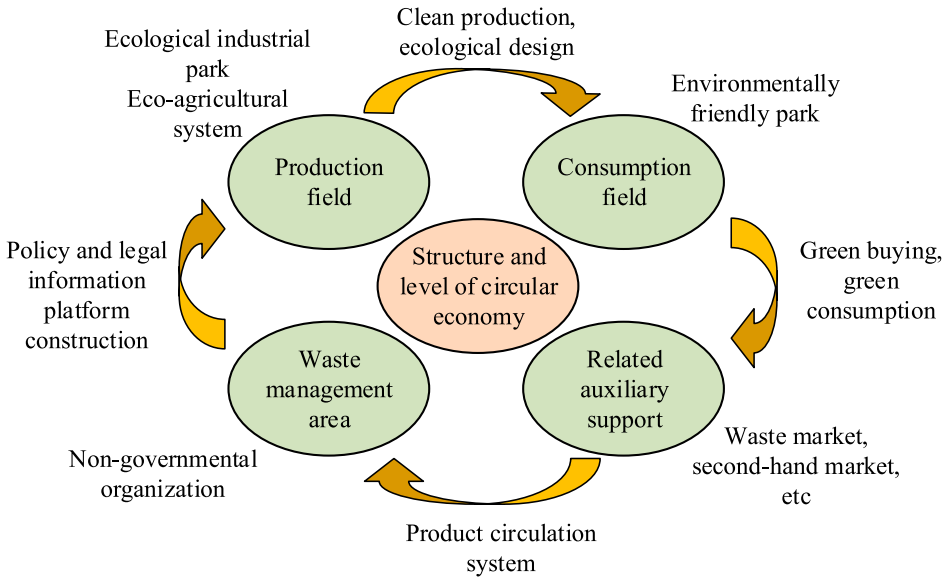


FIGURE 2
Structure and level of CE.

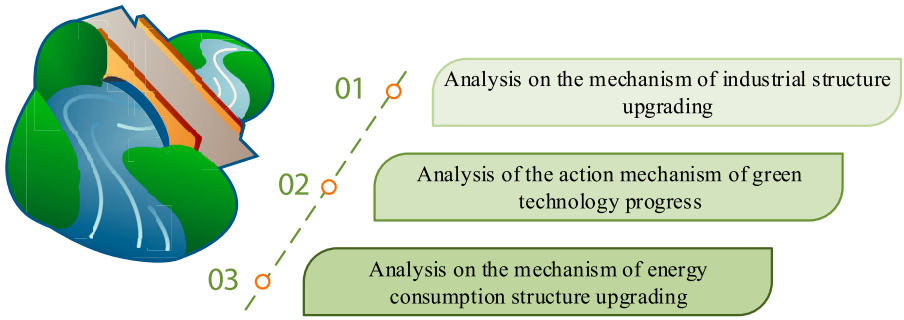


FIGURE 3
Analysis of the impact mechanism of LC.

Based on the understanding and analysis of LC policy, combined with the existing literature and data, a mechanism model is constructed to evaluate the impact of LC policy on the development of CE. The impact mechanism of LC pilot policies is shown in Figure 3.

Figure 3 mentions three impact mechanisms of LC. For industrial structure upgrading, the pilot policies for LC focus on developing green industries, especially industries with minimal environmental impact, such as modern service industries, optimizing industrial structure, and increasing output. The optimization and upgrading of the industrial structure to a certain extent promotes changes in consumer demand, accelerates the transformation of traditional high-energy-consuming and high-emission industries into clean and environmentally friendly industries. Under the context of carbon neutrality, green technological progress can promote core technologies, such as comprehensive utilization of waste, material recycling, green ecological product design, and green high-end equipment re-manufacturing in the CE. Breaking through technological barriers in the development of CE, accelerating the popularization and mature application of green technologies, and reducing the technological gap between China and the world in CE. From an energy perspective, the promulgation of pilot policies for LC can adjust the city's energy consumption structure to some extent. On the one hand, the energy price mechanism can regulate China's energy efficiency. Under certain cost conditions, enterprises will reduce their investment in energy resources by increasing the utilization of funds and other production factors, thereby improving their production efficiency. At the same time, as energy consumption levels increase, there will be a continuous decrease in enterprise demand for energy. This will prompt enterprises to continuously innovate their technologies, achieve optimal allocation of production factors and resources, and thus reduce adverse impacts on the environment.

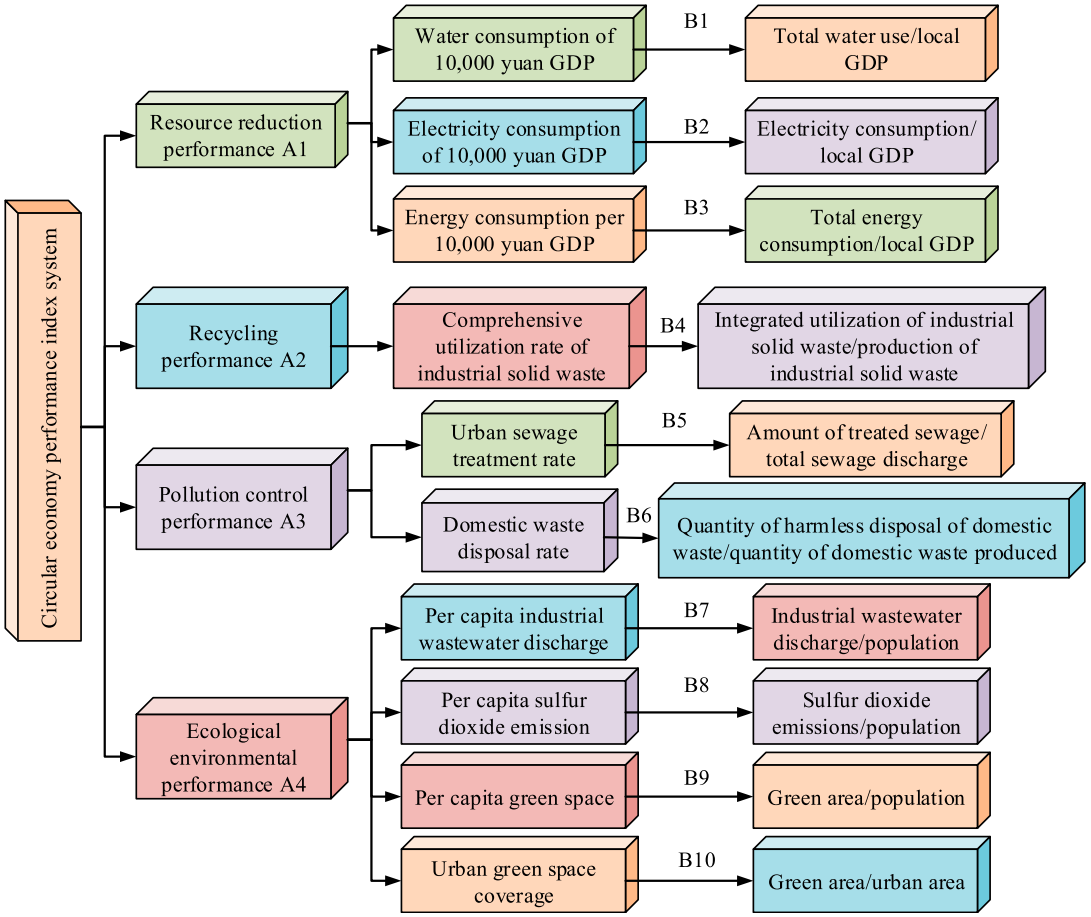


FIGURE 4
Performance index system of CE.

3.2 Comprehensive measurement method for the development level of urban CE

To objectively evaluate the level of CE development in cities, a scientific and comprehensive evaluation index system is established to monitor and analyze its progress and characteristics (Rodríguez-Antón et al., 2022; Ye et al., 2022). The CE uses 3R (reduction, reuse, and recycling) to achieve effective utilization of resources (Wang et al., 2021; Han et al., 2022). Throughout the entire process of production and consumption, efforts should be made to minimize resource waste, minimize damage to the ecological environment, and achieve the best balance between economy and environment. In this regard, this study refers to relevant national policies and draws on the research achievements of scholars such as Wang Xiaohong (Ramon et al., 2023). The constructed performance evaluation index system for urban CE is shown in Figure 4.

In Figure 4, the indicator system for measuring CE studied includes target layer, criterion layer, and indicator layer. The 10 basic indicators correspond to each target layer and standard layer, reflecting the specific level of urban CE development. The AHP is a weight calculation method that combines subjective and objective factors to measure the development level of CE (Akinbobola and Fafure, 2021; Ismail and Ouahrani, 2022). The specific operation is as follows: first, a judgment matrix is established. Assuming that the primary indicator A has n indicators B_n.

In Table 1, b_{ij} is the ratio of the importance of B_i to B_j. After comparing the factors in the same layer with each other by experts, weight scoring is performed. 1–9 is used to represent the relative importance of each indicator, and this matrix satisfies $b_{ij} = 1, b_{ij} \times b_{ij} = 1$. Due to the objectivity of expert scoring results, the judgment consistency is tested. The consistency check formula is shown in Equation (1) (Ramsey et al., 2022).

$$C.I. = (\lambda_{\max} - n)/(n-1) \tag{1}$$

In Equation 1, $\lambda_{\max}$ represents the maximum matrix eigenvalue, which is solved using the set averaging method. First, the geometric mean of each row element is calculated using Equation 2 (Sun and Li, 2021).

$$\overline{w_i} = \sqrt[n]{\prod_{j=1}^{n} b_{ij}} \tag{2}$$

Then the calculation of weights is standardized, as shown in Equation 3 (Enzai et al., 2022).

TABLE 1 Judgment matrix.

A	B_1	B_2	...	B_n
B_1	b_{11}	b_{12}	...	b_{2n}
B_2	b_{21}	b_{22}	...	
...	...	...	...	...
B_n	b_{n1}	b_{n2}	...	b_{nn}

$$w_i = \frac{\overline{w_i}}{\sum_{i=1}^{n}\overline{w_i}}, i = 1, 2, \ldots, n \tag{3}$$

Afterwards, each column element S_j is summed and the value of the maximum eigenvalue is finally calculated as shown in Equation 4 (Maurício et al., 2021).

$$\begin{cases} S_i = \sum_{i=1}^{n} b_{ij}, j = 1, 2, \ldots, n \\ \lambda_{\max} = \sum_{i=1}^{n} w_{w_i s_j} \end{cases} \tag{4}$$

When measuring the consistency, the consistency ratio is calculated. Its consistency is inversely proportional to the result value. The lower the result value, the higher the consistency. The calculation of consistency ratio is shown in Equation 5 (Lacerda et al., 2021).

$$C.R. = C.I./R.I. \tag{5}$$

In Equation 5, $R.I.$ represents the average consistency index. If $C.R. < 0.1$, the judgment matrix has good consistency. If $C.R. > 0.1$, it means that the matrix consistency is poor and needs to be readjusted by experts. Each column of the judgment matrix is standardized as shown in Equation 6.

$$\overline{b_{ij}} = \frac{b_{ij}}{\sum_{i=1}^{n} b_{ij}} \tag{6}$$

Each row of elements is summed up again, as shown in Equation 7.

$$\overline{M_i} = \sum_{j=1}^{n} \overline{b_{ij}} \tag{7}$$

Afterwards, the standardization process is performed as shown in Equation 8.

$$w_i = \frac{\overline{M_j}}{\sum_{j=1}^{n} \overline{M_j}} \tag{8}$$

Based on the above process, the final feature vector $w = (w1, w2, \ldots, w_n)^T$, which is the relative weight vector, can be obtained. The entropy method can effectively utilize the information in the original data, reflect the comprehensive relationship between various indicators, and ensure the reliability of the weighted results (Yang and Yan, 2021). Assuming there are m evaluation objects and n evaluation indicators, the evaluation indicator value is x_{ij}. First, dimensionless processing is performed on the indicators, as shown in Equation 9.

$$x_{ij}^{'} = \frac{x_{ij} - x_{\min} \Big/ x_{\max} - x_{ij}}{x_{\max} - x_{\min}} \tag{9}$$

Then indicator translation is performed to eliminate negative values, as shown in Equation 10.

$$x_{ij}^{''} = x_{ij}^{'} + h \tag{10}$$

In Equation 10, h represents the translation amplitude, usually at 1. Then the proportion R_{ij} of indicator $x_{ij}^{''}$ is calculated using Equation 11.

$$R_{ij} = \frac{x_{ij}^{''}}{\sum_{i=1}^{m} x_{ij}^{''}} \left(0 \le R_{ij} \le 1\right) \tag{11}$$

The entropy value e_j of indicator j is calculated again, as shown in Equation 12.

$$e_i = -\left(\frac{1}{\ln m}\right) \sum_{i=1}^{m} R_{ij} \cdot \ln R_{ij}, e_j \in [0, 1] \tag{12}$$

Then the coefficient of difference g_j for indicator j is calculated. Larger value means higher indicator importance. Finally, j's weight is obtained, and the process is shown in Equation 13.

$$\begin{cases} g_i = 1 - e_j \\ w_i = \frac{g_i}{\sum_{j=1}^{n} g_i = 1} = \frac{1 - e_j}{\sum_{j=1}^{n} (1 - e_i)} \end{cases} \tag{13}$$

3.3 Construction of an evaluation model for the effect of LC on the development of CE based on multiple time-point DID

The dependent variable selected for the study is the level of urban CE development (UE) (Gan et al., 2023). Referring to relevant national policies and previous research results, a system for urban CE development is constructed. On this basis, the study also uses the AHP and entropy method to calculate the weights of secondary and tertiary indicators, respectively (Chen et al., 2022; Li, 2024). By weighted calculation, UE is obtained in prefecture-level cities. The study takes the LC as the core explanatory variable, sets policy grouping simulation variable du based on whether the city is listed as LC, and sets policy time dummy variable dt based on the policy issuance time. The interaction term between du and dt is used as the core explanatory variable. To ensure results' credibility, the study retains data from 273 prefecture-level cities through screening and exclusion. To control for the impact of other factors on regional CE, the study uses urban level characteristics as control variables and selects 7 evaluation indicators. The specific indicators and their meanings are shown in Figure 5.

Due to the fact that public policies are usually formulated by the central government, they can largely avoid selection bias in empirical measurement and reduce endogeneity issues caused by bidirectional causality (Budziński and Czajkowski, 2022). The DID

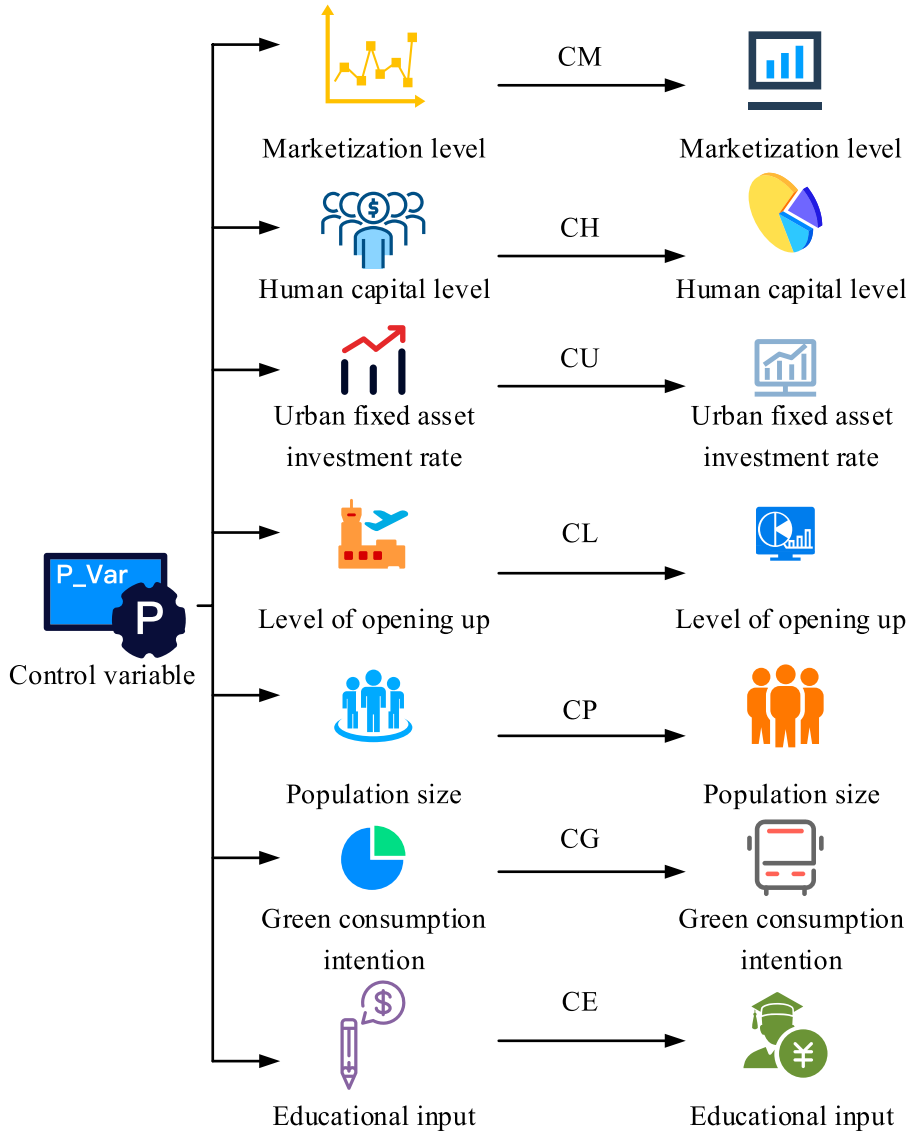


FIGURE 5
Indicators and meanings of influencing factors of regional CE development level.

model is one of the mainstream methods for analyzing the effects of public policies in China. Compared to the traditional DID model, the multiple time-point DID model can process the policy implementation effect at multiple time points, so it is more suitable for the time span and data characteristics of this study. The DID model compensates for the shortcomings of traditional econometric methods by adding a dummy variable at the time level, which can improve the model accuracy. The standard setting is shown in Equation 14.

$$y_{it} = \alpha + \gamma D_t + \beta Treat_i + \delta D_i \times Treat_i + \varepsilon_i (i = 1, 2, \ldots, n) \quad (14)$$

In Equation 14, y_{it} represents the object of policy effect evaluation, and D_t represents the time dummy variable (0 or 1). $Treat_i$ represents a policy dummy variable (0 or 1). δ represents the policy effect. Figure 6 shows the policy effects of the DID model (Guo et al., 2024).

The study regards LC as a quasi natural experiment and uses a multiple time-point DID model to test the impact of LC pilot policies on the development of urban CE (Khuu et al., 2023; Zhao et al., 2022). Firstly, two dummy variables du and dt are generated. Pilot cities are defined as 1 and non-pilot cities as 0. The policy is defined as 0 before implementation and 1 after implementation. The coefficient of $du \times dt$ is the policy effect size, and the regression model is set as Equation 15.

$$CE_{it} = \alpha + \beta du \times dt + \sum b_j X_{it} + \mu_i + \nu_i + \varepsilon_{it} \quad (15)$$

To ensure empirical results' robustness, the study selects a fusion PSM and a multiple time-point DID model for hypothesis testing. Firstly, based on the propensity score, the nearest neighbor matching method is used to find control groups that are similar to the experimental group. Then, the matched two groups are regressed to minimize the selection bias between two groups, and

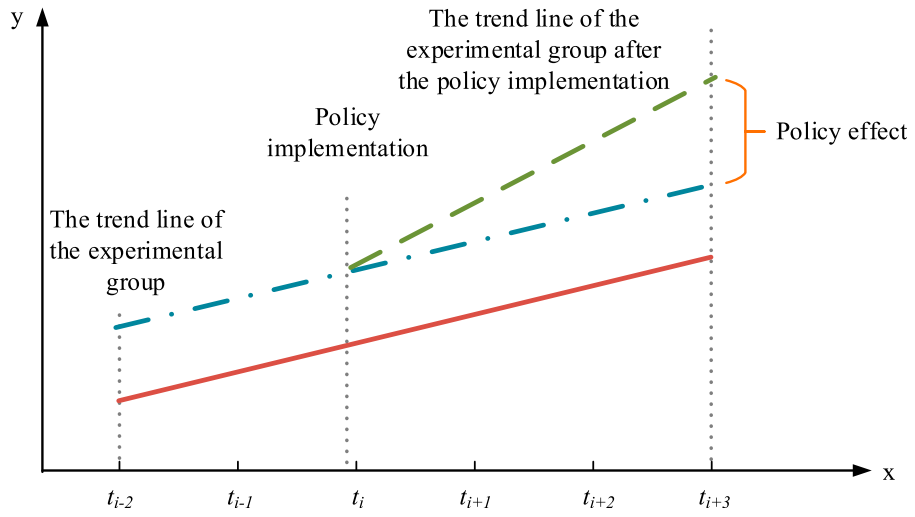


FIGURE 6
DID diagram.

to obtain the purity of policy effects. By referring to relevant environmental practice cases, the impact of experimental plans on the environmental development of Chinese cities can be more accurately evaluated. The specific model is shown in Equation 16.

$$UE_{it}^{PSM} = \alpha + \beta du \times dt + \sum b_j X_{it} + \mu_i + \nu_i + \varepsilon_{it} \quad (16)$$

In Equation 16, i, t represent the city and year. UE is the dependent variable, and X_{it} represents a series of control variables. μ_i, ν_i represents time control effect and urban control effect, respectively. ε_{it} represents the random disturbance term of the system. β represents the impact of LC construction on CE. If $\beta > 0$, it represents promoting development. The mediation effect model is a method for analyzing and studying the process and mechanism of the influence of independent variables on dependent variables (Okorie et al., 2018). The variable relationship of the mediating effect is shown in Figure 7.

In Figure 7, there are two forms of influence of the independent variable on the dependent variable. The dependent variable Y in Model 1 only has X and the control variable $e1$, and the impact effect at this time is the coefficient c of X. At the same time, there is another influencing path, that is, X affects Y through the mediating variable M. The premise for this influence path to hold is that the coefficient of X's influence on M, a, and the coefficient of M's influence on Y, b, are both significant. At this point, the magnitude of the influence effect is the coefficient $a \times b$, and the total effect of X on Y is $a \times b + c'$. To explore the mediating mechanism of LC on the development of CE and understand the proportion of mediating effects in the total effect, a mediating effect model is constructed as shown in Equation 17.

$$\begin{cases} M_{i,t} = \beta_0 \times \beta_1 du \times dt + \sum \beta_j X_{it} + \mu_i + \nu_i + \varepsilon_{it} \\ CE_{i,t} = \gamma_0 \times \gamma_1 du \times dt + \gamma_2 M_{i,t} + \sum \gamma_j X_{it} + \mu_i + \nu_i + \varepsilon_{it} \end{cases} \quad (17)$$

In Equation 17, $M_{i,t}$ represents the mediator variable. If the coefficients of mediating variables β_1 and γ_2 are both significant, it indicates that LC can influence the development level of urban CE by influencing the corresponding mediating variables. If they are not significant at the same time, the selection of the mediating variable is inappropriate.

4 Empirical analysis of the impact of LC on CE development

Based on data from China Urban Statistical Yearbook during 2012–2022, 273 prefecture-level cities are selected to assess the impact of LC pilot policies on CE development. AHP and entropy method are used to measure the development level of CE, and multiple time-point DID model is used to evaluate the policy effect. Policy dummy variable and time dummy variable and their interaction terms are introduced into the model as the core explanatory variables. The robustness test is carried out by PSM method combined with multiple time-point DID model to reduce the selection bias and ensure the reliability of the results.

4.1 The dynamic effect test results of LC pilot policies

The data for the indicators of the CE performance index system in the experiment are sourced from the "China Urban Statistical Yearbook," regional statistical yearbooks, and statistical bulletins. The data collection period spans from 2012 to 2022. The weights of each indicator in the CE index system are determined using the AHP and Entropy Method. The weight results are shown in Figure 8.

In Figure 8B, among the criterion layer, the indicator with the highest weight proportion is the reuse performance, with a weight value of 0.4555. This indicates that this indicator has the greatest impact on CE development. From Figure 8A, among the indicator layer, B1, B2, and B3 have the highest weight values, accounting for 0.2475, 0.2578, and 0.2381, respectively. The weight values of the remaining indicators range from 0.11 to 0.19. After determining the weights, the weighted function is used to measure the development

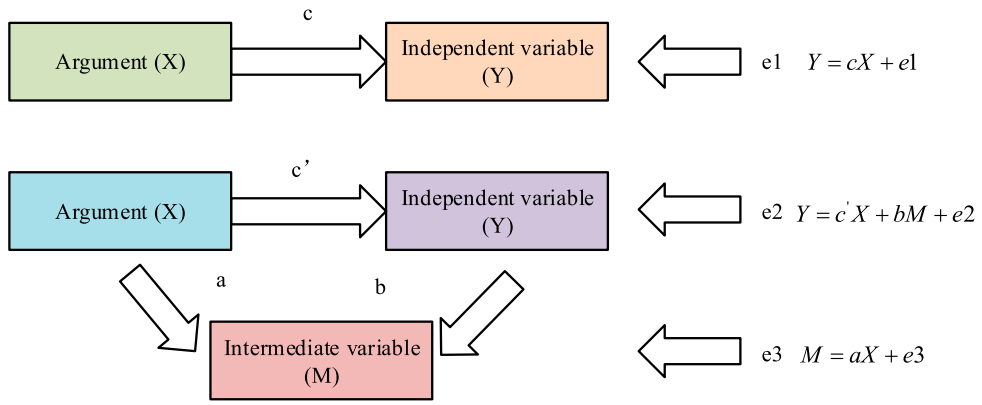


FIGURE 7
Variable relationship of mediating effect.

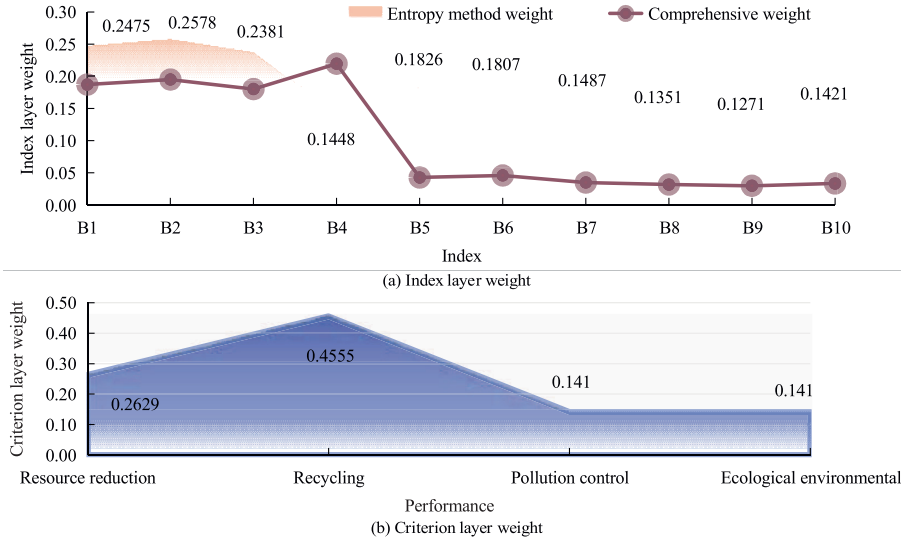


FIGURE 8
Weight results. **(A)** Index layer weight **(B)** Criterion layer weight.

performance of the CE in 273 prefecture-level cities from 2012 to 2022. The results are shown in Figure 9.

Figure 9 reveals that the eastern and central regions show an upward trend in CE, with improvements in their CE performance from 2012 to 2022. The central region, in particular, demonstrates significant progress in CE development, gradually catching up with and surpassing the eastern region. The overall CE performance in the western and northeastern regions is far behind that of the central and eastern regions, especially the northeastern region. In general, significant differences show in CE's spatial development in China. The central and eastern regions exhibit the most noticeable progress and are generally at a higher level nationally. However, the overall CE is still in the primary stage and developing at a relatively slow pace. Therefore, it is necessary to strengthen urban energy-saving construction and formulate corresponding energy-saving development strategies based on regional analysis.

4.2 Test results of the intermediary mechanism of the impact of LC on CE

The study selects 11-year equilibrium panel data of 273 cities in China from 2012 to 2022. Based on this, the urban CE development level index is used as the basis for calculating the dependent variable. The sample size for each variable is 3,000, and the results for the corresponding important variables are shown in Figure 10.

From Figure 10, UE represents the dependent variable, the level of urban CE development. The mean value of UE is 0.334, with a standard deviation of 0.0869. The maximum and minimum values are 0.776 and 0.058. The other variables are control variables, with CH having the smallest mean value of −10.52 representing the level of human capital. The largest mean value belongs to CL, representing the level of openness, with a value of 9.853. The mean values of the other control variables range from −5 to 10.

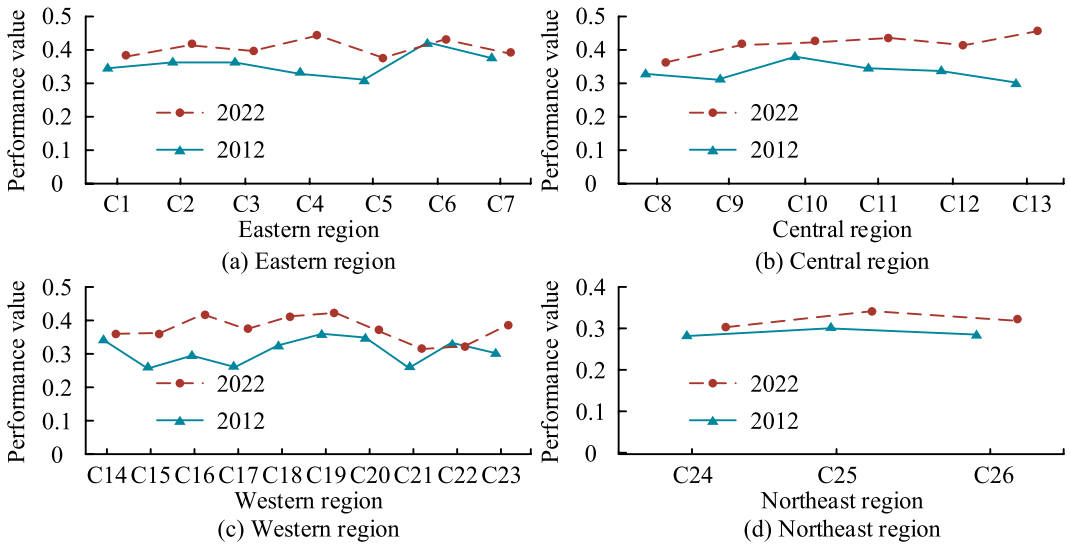


FIGURE 9
Comparison of CE development in different regions. **(A)** Eastern region **(B)** Central region **(C)** Western region **(D)** Northeast region.

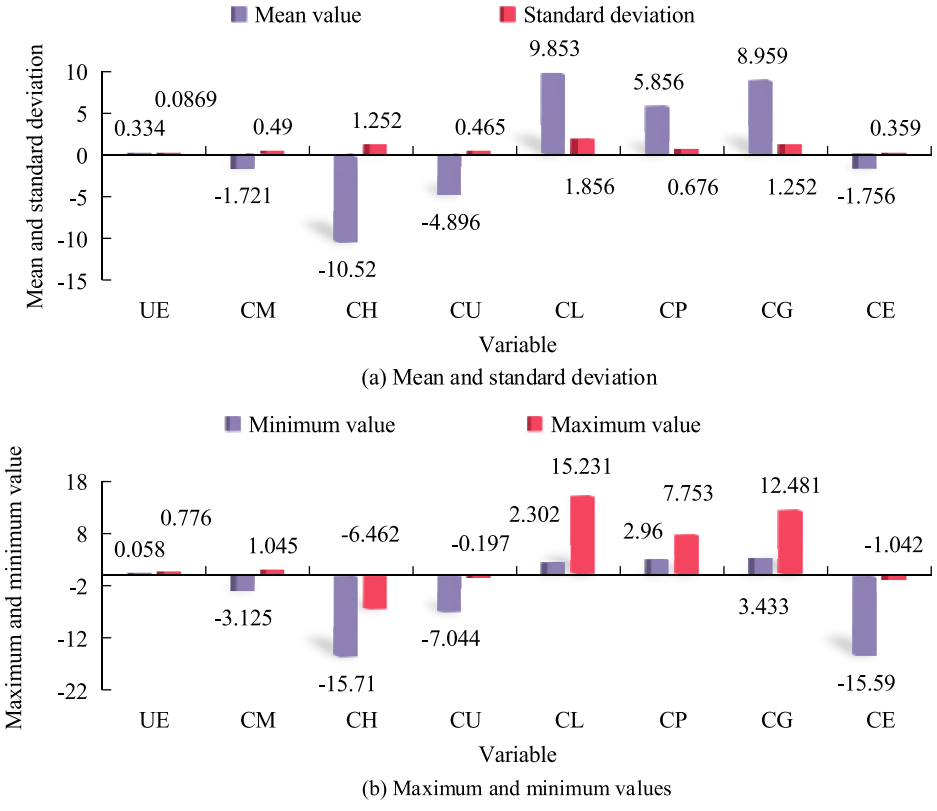


FIGURE 10
Descriptive statistical results of variables. **(A)** Mean and standard deviation **(B)** Maximum and minimum values.

Based on the data mentioned above, the regression results obtained using the multiple time-point DID model are shown below.

From Table 2, the coefficients of each explanatory variable reach a significance level of 1%, indicating a significant improvement in the level of CE development in LC in China without controlling for other variables. Through the analysis of the correlation between the indicators, it is found that when control variables are introduced, the level of urban CE

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TABLE 2 Regression results of the benchmark model.

Ariables	UE1	UE2
DID	0.0668[a]	0.0619[a]
CM	—	0.0114[a]
CH	—	0.00382[b]
CU	—	0.0210[a]
CL	—	0.00673[a]
CP	—	0.0272[a]
CG	—	−0.0101[a]
CE	—	0.00196
Constant	0.326[a]	0.357[a]
Time-fixed effect	Yes	Yes
Regional fixed effect	Yes	Yes
Observations	3,000	3,000
R-squared	0.033	0.115

[a]means that the test is significant at the 1% level.
[b]means that the test is significant at the 5% level.

development increases significantly by 6.3%. Regression analysis of the sample data reveals that most control variables positively impact the regional CE development level, indicating that the selected control variables in the study are reasonable. To eliminate systematic biases caused by interfering factors between two groups, the PSM-DID method is used for robustness testing. P and A represent pre-matching and post-matching, respectively. The results are shown in Figure 11.

In Figure 11A, the absolute value of the standard deviation of the matched variables is all less than 10%, which is significantly lower than before matching. In Figure 11B, the deviation change rates of most variables are above 90%. Only the deviation change rate of the fixed asset investment rate for the city is negative, at −22.2%. In addition, after matching, the t-statistics are not significant. This indicates no significant difference between two groups after pairing, and the paired samples ensure the randomness of the sample, verifying that the PSM conforms to the balance hypothesis. Based on the city variables retained by PSM, a multiple time-point DID model is performed again. Regression results are shown in Table 3.

From Table 3, after solving endogeneity through the PSM-DID model, the LC still improves CE development in cities. After controlling for variables, the LC construction improves the performance of urban CE development by about 6.42%. The results are significant at the 1% level and are consistent with previous empirical results. This shows that LC's implementation promotes China's urban CE development. The intermediary effect of industrial structure rationalization are shown in Table 4.

From Table 4, SR5 and SR6 show the regression results of Equation 17. The coefficients of DID have reached the significant level of 1%, indicating that establishing LCs in China can effectively promote the coordinated development among the first, second, and third industries in the region. From UE7 and UE8, after introducing control variables, the coefficients of social support and social

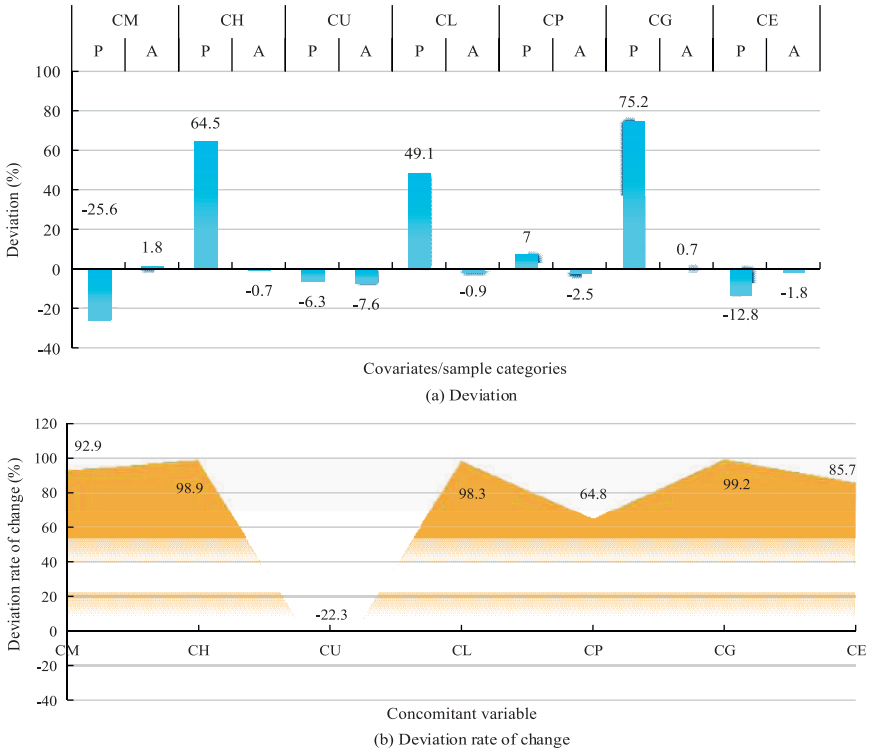


FIGURE 11
Balance test. **(A)** Deviation **(B)** Deviation rate of change.

TABLE 3 Regression results of the PSM-DID model.

Ariables	UE3	UE4
DID	0.0660[a]	0.0640[a]
CM	—	0.00564
CH	—	0.00795[a]
CU	—	0.0127[b]
CL	—	0.00746[a]
CP	—	0.0327[a]
CG	—	−0.0184[c]
CE	—	0.00263
Constant	0.320[a]	0.382[a]
Time-fixed effect	Yes	Yes
Regional fixed effect	Yes	Yes
Observations	872	872
R-squared	0.094	0.180

[a]means that the test is significant at the 1% level.
[b]means that the test is significant at the 5% level.

TABLE 4 Rationalization of industrial structure.

Ariables	SR5	SR6	UE7	UE8
DID	0.300[a]	0.175[a]	0.0568[a]	0.0545[a]
CM	—	0.613[a]	—	−0.0142[a]
CH	—	0.170[a]	—	−0.00336[b]
CU	—	−0.174[a]	—	0.0283[a]
CL	—	0.0025	—	0.00662[a]
CP	—	0.204[a]	—	0.0185[a]
CG	—	0.0274[a]	—	−0.0112[a]
CE	—	0.0107	—	0.00150
SR	—		0.0331[a]	0.0420[a]
Constant	0.928[a]	1.497[a]	0.294[a]	0.294[a]
Time-fixed effect	Yes	Yes	Yes	Yes
Regional fixed effect	Yes	Yes	Yes	Yes
Observations	3,000	3,000	3,000	3,000
R-squared	0.018	0.262	0.080	0.170

[a]means that the test is significant at the 1% level.
[b]means that the test is significant at the 10% level.

support degree are positive and significant at the 1% level. This indicates that under the condition of maximizing the output of the first, second, and third industries, the optimization of the regional industrial structure is promoted, and the rationalization of the industrial structure plays a partial intermediary effect. The empirical results of the intermediary effect model of green technology progress are shown in Table 5.

From Table 5, DID's coefficient is significantly positive from the regression results of TC9 and TC10. This shows that LC construction can improve the regional green technological innovation ability. From the two columns of UE11 and UE12, the effect of green technology progress on CE development reaches the significant level of 1%, regardless of whether control variables are introduced or not. This means that LC pilots can promote China's overall factor green technology progress and thus promote the development of CE. Table 6 shows the empirical results of the intermediary effect model of energy consumption structure upgrading.

From Table 6, at a confidence level of 1%, the impact of LC pilot policy on energy consumption structure is positive, indicating that LC construction significantly optimizes the adjustment of energy consumption structure. Further examination reveals a significant positive correlation between LC and the coefficient of energy consumption structure. This means that LC policies reduce coal and other energy consumption, that is, optimize the energy consumption structure, thereby promoting urban CE, which is consistent with the expected conclusions of the research.

TABLE 5 Empirical results of the intermediary effect model of green technology progress.

Ariables	TC9	TC10	UE11	UE12
DID	0.149[a]	0.141[a]	0.0630[a]	0.0585[a]
CM	—	0.00256	—	−0.0108[a]
CH	—	0.00371[a]	—	−0.00292[a]
CU	—	−0.00655[b]	—	0.00710[a]
CL	—	0.00654[a]	—	0.0256[b]
CP	—	0.000954	—	−0.00994[a]
CG	—	−0.000458[a]	—	0.00207
CE	—	0.0107	—	0.00150
TC	—		0.254[a]	0.242[a]
Constant	0.989[a]	1.048[a]	0.0740[a]	0.102[a]
Time-fixed effect	Yes	Yes	Yes	Yes
Regional fixed effect	Yes	Yes	Yes	Yes
Observations	3,000	3,000	3,000	3,000
R-squared	0.002	0.010	0.068	0.147

[a]means that the test is significant at the 1% level.
[b]means that the test is significant at the 5% level.

5 Discussion and suggestions

This paper constructs a model of the impact of LC pilot policies on the development of urban CE. Using the panel data of 273 prefecture-level cities from 2012 to 2022, this paper analyzes the impact of LC construction on the development of CE through the multiple time-point DID model. The results show that the CE development level of low-carbon pilot cities has been significantly improved, and the increase rate is 6.3% when other variables are controlled. Further robustness test through the PSM-DID model confirms that this policy significantly improves the city's CE development performance, about 6.42%. Yu and Zhang, (2021) also proved that the LC pilot policy

TABLE 6 Results of intermediary effect of upgrading energy consumption structure.

Ariables	EC13	EC14	UE15	UE16
DID	0.0537[a]	0.0468[a]	0.0658[a]	0.0611[a]
CM	—	0.0615[a]	—	−0.0104[a]
CH	—	−0.0198[a]	—	0.00415[b]
CU	—	−0.00888	—	0.0211[a]
CL	—	0.0118[a]	—	0.00653[a]
CP	—	−0.0393[a]	—	0.0278[a]
CG	—	−0.0170[a]	—	−0.00990[a]
CE	—	0.0107	—	0.00150
EC	—	0.0115	—	0.00176
Constant	−0.207[a]	−0.0731	0.330[a]	0.358[a]
Time-fixed effect	Yes	Yes	Yes	Yes
Regional fixed effect	Yes	Yes	Yes	Yes
Observations	3,000	3,000	3,000	3,000
R-squared	0.010	0.046	0.037	0.117

[a]means that the test is significant at the 1% level.
[b]means that the test is significant at the 5% level.

significantly improved the efficiency of carbon emission reduction by combining the DID method with the PSM method. Wen et al. (2022) found that the LC pilot policy significantly improved the carbon emission efficiency through the PSM method and DID method. Consistent with the above findings, the study further validates the positive economic and environmental impacts of pilot LC policies. This paper uses the method of the AHP and entropy to construct the evaluation index system of urban CE development, which makes up for the shortage of a single evaluation system in previous studies. The effectiveness of the LC pilot policy is more accurately verified by the multiple time-point DID and PSM method, and the robustness of the results is ensured. For the first time, from the three aspects of industrial structure rationalization, green technology innovation, and energy consumption structure optimization, the mediation effect of LC pilot policy on CE development is analyzed in detail. This provides a more specific reference for policy formulation.

6 Conclusion

To address the problem of economic development constraints on the environment and resources while climate change is taking place, the net effect of LC on urban CE development was explored. This study used a scientific method combining the AHP and entropy weight to calculate the level of CE development in cities at all levels in China. Based on this, the CE development in all regions of the country was evaluated. Using panel data from 273 provinces and cities from 2012 to 2022, the multiple time-point DID model and intermediary effect model were adopted to analyze LC's effect on urban CE development. The LC pilot policy has promoted the coordinated development of primary, secondary and tertiary industries in the region, optimized the industrial structure, and improved economic benefits and environmental quality. This policy reduced industries with high pollution and high energy consumption, encouraged the development of green industries, and significantly promoted the innovation and application of green technologies. It also improved resource utilization efficiency, reduced environmental pollution, and promoted the development of energy conservation and emission reduction. Based on this, the following suggestions are put forward: First, the coverage of LC pilot should be expanded to more small and medium-sized cities and underdeveloped areas to improve the national CE level. Second, it is necessary to strengthen cooperation and exchange across provinces, cities, and counties, establish regional cooperation mechanisms, share green technologies and management experiences, and promote common development. Third, the energy pricing system should be improved, and a new energy pricing mechanism should be established to guide the rational use of energy. Fourth, research and development investment in green technologies, especially in the fields of energy conservation, environmental protection, and clean energy, should be increased. Policy incentives and financial support should be provided to encourage technological innovation and enhance international competitiveness. Fifth, according to the resource endowment and development needs of each region, scientific development plans should be formulated to promote the green industry to become a pillar industry. Finally, the promotion and education of environmental protection and low-carbon lifestyle should be strengthened, thereby forming a green development pattern of multi-party cooperation. Although this study covers 273 prefecture-level cities nationwide, differences in economic foundation, policy implementation, and environmental conditions may affect universality. Future research should use data with longer time spans and consider regional differences to develop more targeted policy recommendations.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SX: Supervision, Writing–review and editing. YL: Investigation, Writing–original draft. JR: Investigation, Writing–original draft. WW: Investigation, Writing–original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Measurement, dynamic evolution and pollution emission effects of the coupling of green finance and digital technology-evidence from China

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This study uses the game theory combination weighting method to measure the level of coordinated development of green finance and digital technology coupling in China. An analysis was conducted using the Kernel density estimation method, traditional Markov chain model, and spatial Markov chain model to study the dynamic evolution characteristics and trends of the coupling and coordination level of green finance and digital technology in Chinese provinces. The results showed an upward trend in the coupling and coordination level of green finance and digital technology in the entire sample of Chinese, eastern, central, western, and northeastern provinces. Additionally, there is an observable club convergence phenomenon in the coordinated development of green finance and digital technology. The phenomenon of high-level convergence and low-level convergence is significant. The areas on the diagonal that are low-level and high-level have a higher probability of remaining stable. The Markov chain model and the spatial Markov chain model both show the "Matthew effect" in the level of coupling and coordinated development of green finance and digital technology. Empirical testing suggests that the coordinated horizontal development of green finance and digital technology can significantly promote pollution emission. Further analysis found that the coupling and coordination of green finance and digital technology achieves pollution emission by driving green innovation.

KEYWORDS

game theory combination empowerment, green finance, digital technology, coupling coordination, Markov chain model

1 Introduction

Since the 1960s, the world has faced significant ecological and environmental challenges such as global warming and degradation (Hao et al., 2018; Chiu and Lee, 2020; Wang et al., 2022; Wen et al., 2022). The "Global Climate Status in 2023" report released by the World Meteorological Organization in March 2024 shows that records in greenhouse gas levels, surface temperature, ocean heat and acidification, sea level rise, Antarctic sea ice sheet and glacier retreat have been broken again. 2023 is the hottest year on record, with the average annual temperature 1.45°C ± 0.12°C higher than the pre-industrial level (1850–1900), far exceeding the warming range of the previous hottest year and further approaching the 1.5°C temperature control target set by the Paris Agreement. To solve the risks caused by

environmental degradation and promote sustainable development, many countries have started to formulate relevant green development policies from the economic level to promote the coordinated development of the economy and the ecological environment. China, which has made remarkable progress in economic development since the reform and opening up in 1978 (Lee et al., 2021a), also faces environmental pollution and resource shortage problems due to rapid industrialization. On 22 September 2022, China announced its plan to achieve carbon neutrality by 2060, which will accelerate the reduction of carbon dioxide emissions. Exploring the path to achieve coordinated development of economy and environment provides ideas for solving the above-mentioned economic and environmental problems, and also provides solutions for other developing countries to achieve green development.

In the process of economic development, achieving green development by reducing pollution and emissions can not only promote sustainable economic development, but also achieve the ecological goal of harmonious coexistence between man and nature. Finance is an important force in supporting economic development. Green finance has the dual characteristics of financial resource allocation and environmental regulation (Tariq and Hassan, 2023). Its clear guiding characteristics provide new ideas for easing corporate financing constraints, reducing financial costs and increasing R&D investment. Most existing studies have studied green finance from a single dimension, exploring its pollution reduction effect (Simionescu and Gavurová, 2023; Zhou et al., 2023). However, information asymmetry makes it difficult for traditional financial institutions to penetrate the environmental benefit information of specific projects, which is not conducive to the development of enterprises to obtain green funds or avoid becoming the target of regulation. At the same time, there is a clear differentiation in the resource allocation decisions of financial institutions under the constraints of environmental goals (Liu and Xu, 2024). The increased risk of environmental regulation has caused banks and other financial institutions to guide credit resources away from polluting enterprises in order to avoid potential financial and reputational losses. This has ultimately led to a dilemma for polluting enterprises that have a strong desire to transform but cannot obtain effective financial support. The development of digital technology can help solve or alleviate such problems. Digital technology has efficient analytical capabilities, which not only breaks the isolation between banks and enterprises, but also provides effective preparation for the mutual sharing of enterprise resources, the absorption and diffusion of external knowledge, and the acceleration of the conception and formation of innovative projects. On the one hand, digital technology effectively reduces the cost of information collection between the supply and demand sides of funds, helps to solve the problem of "difficult and expensive financing" in the process of green transformation of enterprises, and enables financial institutions to better serve green development. On the other hand, through the establishment of a green finance monitoring and evaluation system through digital technology, the energy conservation and emission reduction, green transformation and pollution control effects of green finance can be comprehensively quantified, and the mismatch of green financial resources flowing to industries can be reversed, providing a policy basis for regulatory authorities to implement differentiated supervision and incentive measures. Therefore, promoting the coupled and coordinated development of green finance and digital technology can achieve green technology innovation in enterprises (Liu et al., 2023a), promote the realization of pollution reduction and emission reduction targets, and thus has important significance for achieving green economic transformation and sustainable development.

Existing studies have mainly examined the impact of green finance from two perspectives: environmental regulation and financial resource allocation. On the one hand, from the perspective of environmental regulation, the impact of environmental regulation on enterprises is analyzed based on the Porter hypothesis's induced innovation effect. Some studies believe that environmental regulation has curbed illegal pollution discharge by enterprises, and the improvement of the ecological environment has attracted more investment in high-end service industries and promoted industrial upgrading and transfer (Xiong and Chen, 2022). Market incentive-based environmental regulation uses measures such as carbon emission trading and environmental protection taxes. Through the price mechanism, the cost of environmental pollution is internalized and the expected value of environmental investment is locked in, which encourages enterprises to carry out green activities and achieve green transformation of enterprises (Wu et al., 2024a; Yu and Zheng, 2024). On the other hand, from the perspective of financial resource allocation, the resource allocation effect of green finance on enterprise development is mainly examined from the perspective of green credit policy, green bonds, green financial innovation and green reform pilot (Liu and Xiong, 2022; Yin et al., 2023; Xiong et al., 2023).

Existing studies have confirmed that green finance has a significant impact on pollution reduction. However, the traditional financial model lacks the support of effective technical means and data-driven quantitative measurement, and cannot achieve effective supervision of post-loan funds, and cannot track and judge in a timely manner. The true use of funds and benefits of enterprises cannot accurately identify and screen high-quality green innovation projects, resulting in the insufficient role of green finance in improving the quality of green innovation of enterprises (Wang et al., 2023), which is not conducive to the long-term green development of the economy. In view of this, this study attempts to construct a green finance and digital technology coupling and coordinated development index based on China's actual scenario, judge the degree of coupling and coordination between digital technology and green finance through measurement results, analyze the dynamic evolution characteristics of their coupled and coordinated development, and test their pollution emission effects.

This study has two possible contributions. First, it provides more reliable quantitative measurement evidence for the study of the coupling and coordination of green finance and digital technology. Second, it supplements the relevant research on the impact of the coupling and coordinated development of green finance and digital technology on pollution reduction, and opens up new ideas for achieving pollution reduction and emission reduction goals, promoting the green transformation of the economy, and promoting global sustainable development.

2 Literature review and hypothesis development

2.1 Literature review

To prevent credit risks, the "Opinions on Implementing Environmental Protection Policies and Regulations" were released in July 2007. Since then, China has experienced rapid development in green finance, leading to the creation of a green financial system. This system is primarily comprised of green credit, which is supported by green bonds, green funds, and green insurance. By providing green credit, high-energy-consuming and high-polluting enterprises are able to reduce credit rationing. As a result, air pollutants and carbon dioxide emissions can be suppressed (Tariq and Hassan, 2023). At the 2016 G20 Summit, "green finance" began to receive widespread attention from society. In 2016, the "Guiding Opinions on Building Green Financial System" was issued by the People's Bank of China and other organizations, marking a significant milestone in the development of green finance. It signals a period of rapid growth in this field. The swift growth of green finance has transformed it into a significant instrument for promoting green economic development. As a result, scholars have started to focus more on the definition and assessment of green finance, as well as its influence on both the economy and the environment (He et al., 2019a; He et al., 2019b; Liu et al., 2019; Hu et al., 2021; Lee et al., 2021b).

At present, academic research on the macro-effects of green finance mainly focuses on the effects of green finance on high-quality economic development (Xu and Dong, 2023), low-carbon development (Wara, 2007), and green development (Liu et al., 2019). It also measures and evaluates the level of regional green finance development (Liu et al., 2023a; Jiang et al., 2020).

Based on the perspective of economics, some economists believe that green finance can provide capital support, rationalize economic structures, improve supply-side investment quality, and ultimately lead to more stable economic growth (Lee et al., 2022). Certain scholars conduct research from an environmental perspective and suggest that green finance can facilitate environmental progress, optimize resource utilization, and mitigate pollution and carbon emissions. This type of financing can provide sustainable, dependable financial backing for the advancement of ecological civilization and the attainment of carbon neutrality (Wu et al., 2023; Liu et al., 2020a; Xia and Xu, 2020; Yan et al., 2020; Wang and Ren, 2022). Although some articles touch upon the pollution control and emission reduction effects of green finance, most of them simply consider it as a part of sustainable development, green economic efficiency, and circular economy (Simionescu and Gavurová, 2023; Chin et al., 2024; Liu et al., 2023b), and do not study it as a separate subject.

Digital technology based on information data processing provides an effective way for sustainable development to achieve pollution reduction and emission reduction through the use of artificial intelligence, cloud computing, and big data. One key consensus in promoting sustainable development and achieving pollution reduction and emission reduction goals is through the vigorous development of green industries and the digital economy. In the field of low-carbon research, digital technology has attracted the attention of many scholars and has become an important research topic (Truong, 2022). Digital technology can alleviate information asymmetry in the field of factor allocation and break barriers to the flow of production factors by exerting value creation effects, network connection effects, resource allocation effects, and cost-saving effects (Xiang and Tian, 2022; Yang et al., 2022; Zhang et al., 2022; Qi and Ren, 2021; Xu et al., 2023; Guo and Qiu, 2020), providing a favorable digital facility platform for the realization of green economic development. Some scholars have analyzed the application of digital technology in the financial sector (Zhao et al., 2023) and its impact on carbon emission intensity (Zhang et al., 2023).

There are few studies on the coupling of green finance and digital technology, and only a few scholars have analyzed the impact of the coupling of green finance and digital technology on corporate green technology innovation (Xiong and Chen, 2022). Therefore, this study measures the level of green finance and digital technology coupling coordination based on the game theory combined weighting method, and analyzes its impact on pollution emission.

2.2 Theoretical analysis and hypothesis

Based on an in-depth analysis of green finance research and discussion of the impact of digital technology, we believe that the coupled and coordinated development of green finance and digital technology can achieve pollution emission reduction through green innovation mechanisms.

Carbon dioxide and air pollutant emissions have the same roots, origins, and processes. Controlling carbon dioxide emissions is an important factor in reducing air pollutant emissions. It is feasible to reduce emissions of both at the same time (Dong et al., 2019; Cheng et al., 2021a).Green credit, as China's most important green financial product, sets clear environmental access thresholds for loan recipients, raising financing costs for high-pollution and energy-consuming industries. Through the resource allocation effect, green credit reduces credit rationing, increases the risk of exiting the market, and releases market selection signals, thereby reducing atmospheric pollutants and carbon dioxide emissions (Bao and He, 2022). With environmental damage and climate warming, investors are beginning to worry about investment failures due to environmental risks and are more willing to buy green bonds, thereby promoting the development of green industries and achieving emission reduction effects (Gianfrate and Peri, 2019; Hu and Chen, 2023).

By building a green project information sharing platform, digital technology effectively reduces the information collection costs between the supply and demand sides of funds, enabling financial institutions to better serve green development, rationally allocate green financial resources, and reasonably avoid capital mismatch. The higher the level of coupling and coordination between green finance and digital technology, the lower the financing costs of enterprises, which can promote enterprises to carry out green transformation and achieve pollution reduction and emission reduction (Xiong and Chen, 2022). Therefore, this study proposes the following hypothesis.

Hypothesis 1. The coupled and coordinated development of green finance and digital technology can reduce pollution and emissions.

The coupling of green finance and digital technology can reduce pollution emissions by promoting green innovation. Green finance has the dual characteristics of environmental regulation and capital allocation. Based on Porter's hypothesis theory, green finance cannot achieve ecological and economic benefits without technological innovation. Green finance can play a role in environmental regulation. By setting environmental access thresholds to restrict external financing, it can increase the pollution emission costs of enterprises. This will guide enterprises to increase their investment in environmental management and improve their production efficiency through effective innovation. While continuously improving environmental benefits and achieving pollution reduction and emission reduction, it will also bring about a continuous increase in the return on capital (Bao and He, 2022; Niu et al., 2022). At the same time, considering that green innovation requires a lot of time and sufficient resource support, problems such as resource mismatch may become the main factor hindering its development (Wu et al., 2024b). Digital technology-empowered green finance can conduct high-quality integration and reallocation of green innovation resources, achieve targeted allocation of green innovation resources, reconstruct the resource allocation pattern, and mobilize local enthusiasm for green innovation. Green innovation can assist the research and development process of green cleaning products, promote the efficient optimization of clean production technology, promote the improvement of carbon dioxide purification technology, rapidly reduce the emission intensity of pollutants, greenhouse gases, industrial wastewater, etc., and promote pollution reduction and emission reduction. In addition, green management innovation can effectively promote the improvement of management processes and infrastructure optimization such as production and research and development, so as to improve labor productivity, reduce carbon emission intensity, and achieve the goal of reducing pollution and emissions. Some studies believe that green innovation can significantly promote carbon emission reduction. Xu et al. (2021) found that green innovation has a significant inhibitory effect on carbon emissions, but the inhibitory effect of carbon sink technology and carbon storage technology is weak. Relevant scholars have found that green innovation in N-11 countries (Wang et al., 2020), G7 countries (Ding et al., 2021), Singapore (Meirun et al., 2021) and BRICS countries (Jiang et al., 2022)can significantly reduce carbon emissions. Therefore, this study proposes the following hypothesis.

Hypothesis 2. The coupled and coordinated development of green finance and digital technology can achieve pollution emission through green innovation.

3 Method and model

3.1 Sample and data

From 2011 to 2020, 30 provinces and municipalities in China were selected as research samples to evaluate their level of coupling and coordination of green finance and digital technology. The data is primarily sourced from various reliable sources including the "China Urban Statistical Yearbook," WIND database, "China Insurance Yearbook," "China Industrial Statistical Yearbook," CSMAR database, and others. Some provinces with a large number of missing data were excluded.

3.2 Method

3.2.1 Construction of indicator system

Early domestic scholars used commercial banks' green credit balances to reflect green finance and study the impact of green finance on commercial banks' credit risks (Sun et al., 2017). To fully reflect the concept of green finance, it's not enough to focus solely on green credit. The development of financial products and the improvement of the green financial system are also important factors to consider. To promote sustainable development, Ren et al. created green financial indicators that cover four key areas: green credit, green securities, green insurance, and green investment (Ren et al., 2020). According to the Development Research Institute at the Southwestern University of Finance and Economics and the Environmental and Economic Policy Research Center of the Ministry of Environmental Protection, green finance has the potential to foster the integration of financial activities, including credit, insurance, securities, and industrial funds, in support of a balanced and sustainable development of the economy, resources and environment (The Study Group of Development Research, 2015). One way to categorize sustainable financing methods is through the five tools of green finance, which include green credit, green securities, green insurance, green investment, and carbon finance. In 2016, several Chinese ministries and commissions, including the People's Bank of China and the Ministry of Finance, collaborated to release "Guiding Opinions on Building a Green Financial System." This document outlines the meaning of green finance across five dimensions: green credit, green investment, green funds, green insurance, and carbon finance. Existing literature has not formed a consistent method for measuring the development level of regional digital technology and green finance, and there are few studies that measure the coordinated development of green finance and digital technology.

To evaluate the level of development in green finance, this study selected six indicators from five dimensions. These dimensions include green credit, green investment, green funds, green insurance, and carbon finance. The selected indicators were based on previous research and were used to construct an evaluation system. Refer to the practices of scholars such as Zhao (2022), Huang et al. (2019), Zhao et al. (2020), and Li (2021), the potential of digital technology can be evaluated through two dimensions: infrastructure and application. By examining these factors, we can gain insight into how to improve and shape a brighter future. Table 1 shows how digital technology and green finance are measured. It's useful for tracking progress and promoting sustainable practices.

3.2.2 Determination of indicator combination weight

3.2.2.1 Subjective weighting method-analytic hierarchy process

1) The weight of the indicator layer to the criterion layer

First, one of the commonly used methods for constructing the judgment matrix A is the 9-scale method. The specific calculation formula is shown in Equation 1. This method involves assigning numerical values from 1 to 9 to represent the degree of importance or preference of each criterion with the others.

$$A = (\alpha_{sr})_{M\times M}(s = 1, 2, \ldots, M; r = 1, 2, \ldots, M) \quad (1)$$

TABLE 1 Construction of indicator system.

First-level indicators	Second-level indicators	Specific indicators	Indicator attributes
Green Finance	Green Credit	Total interest expenses of the six major energy-consuming industries/Interest expenses	-
	Green Securities	Market value ratio of environmental protection companies	+
	Green Insurance	Scale environmental pollution insurance: agricultural insurance income/property insurance income	+
		Environmental pollution insurance compensation ratio = agricultural insurance expenditure/agricultural insurance income	+
	Green Investment	Proportion of investment in environmental governance: investment in environmental governance/GDP	+
	Carbon Finance	Carbon emission loan intensity: RMB loan balance of financial institutions at the end of the year/carbon dioxide emissions	+
Digital Technology	Digital Infrastructure	Total telecommunications business volume	+
		Number of mobile phone users at the end of the year	+
		Number of Internet broadband access ports	+
	Digital Technology Applications	Digital Inclusive Financial Development: China Digital Inclusive Financial Development Index	+

Note: "+" indicates a positive attribute, and "-" indicates a negative attribute.

TABLE 2 Meaning of scale in judgment matrix.

Scale	Meaning
1	The *s*th indicator is equally important as the *r*th indicator
3	The *s*th indicator is slightly more important than the *r*th indicator
5	The *s*th indicator is significantly more important than the *r*th indicator
7	The *s*th indicator is strongly more important than the *r*th indicator
9	The *s*th indicator is extremely important than the *r*th indicator
2, 4, 6, 8	In the middle of the above two adjacent comparison scales

Where:

α_{sr} is the judgment scale, indicating the importance of the *s*th indicator relative to the *r*th indicator. Its definition is shown in Table 2.

M is the number of indicators in the criterion layer where the *s*th indicator and the *r*th indicator are located. $\alpha_{sr} = 1/\alpha_{sr}$.

To find the index weight, the eigenvector method is used. The formula used for calculating the weight of the *i*th indicator under the *k*th criterion layer is shown in Equation 2.

$$v_{ki} = v_{ki}^{'} \Big/ \sum_{i=1}^{M} v_{ki}^{'} \tag{2}$$

Where:

v_{ki} is the weight of the *i*th indicator under the *k*th criterion layer to the *k*th criterion layer.

$v_{ki}^{'}$ is the *i*th eigenvector under the *k*th criterion layer corresponding to the maximum eigenvalue of the judgment matrix.

Conduct a consistency test on the results. If the test passes, the weight obtained is reasonable. Otherwise, the judgment matrix needs to be reconstructed to find the weight.

3.2.2.2 The weight of the indicator layer to the overall target layer

According to the AHP weighting principle (Hoque et al., 2017), the weight of the *i*th indicator to the *k*th criterion is shown in Equation 3.

$$\rho_{ki} = v_{ki} v^{(k)} (k = 1, 2, 3; i = 1, 2, \ldots, M) \tag{3}$$

Where:

ρ_{ki} is the weight of the *i*th indicator under the *k*th criterion layer to the overall goal.

v_{ki} is the weight of the *i*th indicator under the *k*th criterion layer to the *k*th criterion layer.

$v^{(k)}$ shows the weight of the *k*th criterion layer to the overall goal.

(2) Objective weighting method—entropy weight method

The objective weight of each dimension indicator is calculated using the entropy weight method. First, to ensure consistency, the indicators that are measured in different units are standardized. The specific calculation formula is shown in Equation 4.

$$Y_{ij} = \frac{x_{ij} - \min\left(x_{1j}, \ldots, x_{nj}\right)}{max\left(x_{1j}, \ldots, x_{nj}\right) - \min\left(x_{1j}, \ldots, x_{nj}\right)} \tag{4}$$

Where:

x_{ij} represents the value of the *j*th indicator in the *i*th region.

Secondly, calculate the proportion of the *i*th region in the *j*th indicator and obtain the information entropy. The specific calculation formula is shown in Equations 5 and 6.

$$q_{ij} = \frac{Y_{ij}}{\sum_{i=1}^{n} Y_{ij}} \tag{5}$$

$$E_j = -\frac{1}{\ln n}\sum_{i=1}^{n} q_{ij} \ln q_{ij} \tag{6}$$

Then, the weight of each indicator has been determined. The specific calculation formula is shown in Equation 7.

$$W_j = \frac{1 - E_j}{\sum\left(1 - E_j\right)} \tag{7}$$

W_j is the weight of j indicator.

Finally, the weights are multiplied by the normalized values. The specific calculation formula is shown in Equation 8.

$$DF_i = \sum_{j=1}^{n} W_j Y_{ij} \tag{8}$$

3.2.3 Game theory combination weighting method

Game theory is the study of conflict and cooperation between decision-makers using mathematical models (Myerson, 1991). Compared to other methods of weighting combinations, the game theory method can minimize the deviation between subjective and objective weights, as well as the combination weighting, and maximize the value of subjective and objective weighting (Zhao et al., 2024a). To achieve the desired outcome, it is crucial to determine the appropriate weight for the combination of analytic hierarchy process and entropy weight method. In this article, the game theory combination weighting method is applied for determining the weight of the indicator system. The specific steps involved in the method are provided below.

Assume that from L perspectives, L methods are used to weight the two index weighting methods respectively and obtain L groups of index weight vectors. Assume that the index weight vector obtained by the ith weighting method is $w_i^T = (w_{i1}, w_{i2}, \ldots, w_{in})$. Where n is the number of three-level indicators under the indicator system, and any linear combination w of L groups of weight vectors is shown in Equation 9.

$$w = \sum_{q=1}^{2} \alpha_q w_q^T = \alpha_1 w_1^T + \alpha_2 w_2^T \tag{9}$$

where:

α_1 is the weighted combination weight of the AHP.

w_1^T is the indicator weight vector determined by the analytic hierarchy process.

α_2 is the weighted combination weight of the entropy weight method.

w_2^T is the index weight vector determined by the entropy weight method.

Using the equilibrium theory of game theory, the optimal solution to the weighted combination weight can be obtained by minimizing the deviation between the subjective and objective weights. This is achieved by minimizing the difference between the indicator weight vector w^* and the indicator weight vector w_i determined by each weighting method. Under this condition, the combined weights α_1^* and α_2^* of the analytic hierarchy process and the entropy weight method can be obtained. The formula is shown in Equation 10.

$$\min\left\|w^* - w_i^T\right\| = \min\left\|\sum_{q=1}^{2} \alpha_q^* w_q^T - w_i^T\right\|, \mathrm{i} = 1, 2$$
$$s.t. \sum_{q=1}^{2} \alpha_q^* = 1 \tag{10}$$

Where:

When $i = 1$, w_i^T represents the indicator weight vector determined by the analytic hierarchy process. When $i = 2$, w_i^T represents the index weight vector determined by the entropy weight method.

Substitute the combined weights α_1^* and α_2^* of the analytic hierarchy process and the entropy weight method into Equation 11 to obtain the index weight vector of the game theory combined weighting method.

$$w^* = \alpha_1^* w_1^T + \alpha_2^* w_2^T \tag{11}$$

3.2.4 Coupling coordination model

The concept of "coupling" was initially introduced into economic analysis from the field of physics. The degree of coupling is a measure of the level of interdependence and mutual constraints between multiple systems. This measurement can be used to evaluate the degree of dynamic correlation between two or more systems. Unlike causal relationship analysis based on econometric models, the coupling degree model does not focus on the causal relationship between two systems but instead concentrates on the dynamic correlation between them. Therefore, in this study, we have utilized the coupling coefficient model from physics to measure the coupling level between green finance and digital technology (Liu et al., 2023a). The specific form is shown in Equation 12.

$$C_{it} = \frac{\sqrt{G_{it} \times D_{it}}}{(G_{it} + D_{it})/2} \tag{12}$$

Where:

C_{it} represents the degree of coupling between green finance and digital technology. The larger the value, the better the coupling between the two, and the stronger the correlation.

In order to more accurately reflect the level of interactive development between green finance and digital technology, it is necessary to further build a coupling coordination model of green finance and digital technology. The specific formula is shown in Equations 13 and 14.

$$C_{0it} = \sqrt{C_{it} \times T_{it}} \tag{13}$$
$$T_{it} = \lambda_i G_{it} + \lambda_j D_{it} \tag{14}$$

λ_i and λ_j are the weights of indicators G_{it} and D_{it}. Since green finance and digital technology are equally important in the development process, the two indicators are given the same weight, that is, $\lambda_i = \lambda_j = 0.5$.

3.2.5 Kernel density estimation

This study uses non-parametric kernel density estimation to analyze the dynamic evolution trend of the coupling coordination level of green finance and digital technology in China. Kernel density estimation has weak dependence on the model and has good

TABLE 3 Markov transition probability matrix (k = 4).

t/t+1	1	2	3	4
1	P_{11}	P_{12}	P_{13}	P_{14}
2	P_{21}	P_{22}	P_{23}	P_{24}
3	P_{31}	P_{32}	P_{33}	P_{34}
4	P_{41}	P_{42}	P_{43}	P_{44}

TABLE 4 Spatial Markov transition probability matrix (k = 4).

Spatial lag	t/t+1	1	2	3	4
k = 1,2,3,4	1	$P_{11\|k}$	$P_{12\|k}$	$P_{13\|k}$	$P_{14\|k}$
	2	$P_{21\|k}$	$P_{22\|k}$	$P_{23\|k}$	$P_{24\|k}$
	3	$P_{31\|k}$	$P_{32\|k}$	$P_{33\|k}$	$P_{34\|k}$
	4	$P_{41\|k}$	$P_{42\|k}$	$P_{43\|k}$	$P_{44\|k}$

statistical properties, and has important applications in studying spatial distribution non-equilibrium. Assuming that the density function of the random variable X has the following form. The specific calculation formula is shown in Equation 15.

$$f(x) = \frac{1}{Nh}\sum_{i=k}^{N} k\left(\frac{x_i - x}{h}\right) \tag{15}$$

Where:

$f(x)$ represents the density function of the coupling coordination level of green finance and digital technology.

N represents the number of observations.

X_i represents independent and identically distributed observations.

k is the kernel function.

h is the smoothing parameter (broadband). The larger h is, the smoother the density function curve is and the greater the estimation deviation is. Therefore, this study will choose a smaller bandwidth while ensuring a beautiful curve.

$$\begin{cases} \lim k(x), x = 0 \\ \int_{-\infty}^{+\infty} k(x)dx = 1, k(x) > 0 \\ \int_{-\infty}^{+\infty} k^2(x)dx < +\infty, \; sup\, k(x) < +\infty \end{cases} \tag{16}$$

The kernel function is a smooth transformation or weighted function that must meet certain conditions as shown in Equation 16. Kernel functions include trigonometric kernel functions, quadrangular kernel functions, Gaussian kernel functions, etc. Empirical research shows that the less grouped data used, the greater the possibility of selecting the Gaussian kernel function (Sala-i-Martin, 2006). Therefore, this article has used the Gaussian kernel function to estimate the evolution trends and distribution dynamics of the coupling coordination level of green finance and digital technology.

3.2.6 Markov chain model

The traditional Markov Chain is a mathematical method that calculates the probability distribution and evolution trend of each type. It does so under the condition that time and state are both discrete. This method can help us explore the dynamic evolution characteristics of the distribution of the coupling and coordinated development levels of green finance and digital technology in different periods. Markov Chains are stochastic processes.

$$\{X(t), t \in M\} \tag{17}$$

The set M of the random process grows exponentially with each period, while the finite state represents the number of states of the random variable. Equation 17 is valid for all periods t and all possible states j and i. Equation 18 states the characteristics of a first-order Markov chain, where the probability of the random variable X being in state j at period t depends solely on the state of X at period t-1.

$$\left\{X_t = j \,\middle|\, X_{t-1} = i_{t-1}, X_{t-2} = i_{t-2}, \cdots X_0 = i_0\right\} = P\left\{X_t = j \,\middle|\, X_{t-1} = i\right\} \tag{18}$$

Let's assume that the state space of the Markov process is represented by the set I, where $I = \{1, 2, 3\}$. The matrix $P = P_{ij}$, $i,j \in I$ represents the state transition probability matrix when the process changes from state i to state j. Table 3 shows the matrix composed of all transition probabilities. This probability can be estimated according to Equation 19.

$$P_{ij} = \frac{n_{ij}}{n_j} \tag{19}$$

Where:

P_{ij} is called the state transition probability matrix.

n_{ij} is the total number of times the state of the observed object transitions from state i in year t to state j in year $t + 1$ during the examination period.

n_j is the total number of occurrences of state j in the initial period.

The Markov chain model overcomes the limitation of kernel density estimation in describing the distribution dynamics of the coordinated development levels of green finance and digital technology coupling. However, it assumes that regions are isolated and does not consider spatial factors. The level of coupled and coordinated development of green finance and digital technology is not isolated in geographical space and is closely related to the development level of surrounding areas. Therefore, the spatial Markov chain model uses the concept of "spatial lag" to examine the impact of spatial factors on the transition probability of the region, thereby determining the spatial status of the region. Based on the traditional Markov chain, k types of spatial lags are used as regional transfer conditions, which will produce k types of $k \times k$ conditional transition probability matrices (Table 4). The spatial transition probability of a region transitioning from state i in year t to state j in the next lag year, conditional on spatial lag type k, is denoted by $P_{ij|k}$.

To calculate the level of adjacent areas in a certain area, the spatial weight matrix is used. That is, $\sum_j w_{ij} y_j$. w_{ij} (i = j = 1,2,3,. . .n) is an element in W. This matrix represents the weight of the observation value in adjacent areas to the spatial lag operator of

position i. y_j represents the level of coordinated development of green finance and digital technology coupling in adjacent region j This study uses the edge distance spatial weight matrix, where 1 is assigned for adjacent provinces, and 0 otherwise. The phenomenon that the level of coupling and coordinated development of green finance and digital technology changes in adjacent types is defined as the transfer. A forward transfer is when a region moves from a low level to a medium-low level, whereas a forward jump transfer is when it moves from a low level to a high level. Similarly, a negative transfer or a negative jump transfer can occur when a region moves from a high level to a level lower than itself.

3.3 Empirical research design

3.3.1 Variable

3.3.1.1 Explained variables

Referring to previous studies (Hu and Chen, 2023), this study measures pollution emission from the perspectives of air pollution and carbon emissions. This study uses *per capita* SO2 to measure air pollution and *per capita* CO2 to measure carbon emissions. The total SO2 emissions and total CO2 emissions are used as replacement variables for robustness testing. The data are logarithmized to avoid the influence of heteroscedasticity.

Based on the estimation method of the 2011 Provincial Greenhouse Gas Inventory Compilation Guidelines (Trial), and taking into account data availability and the actual carbon emission contribution of each energy source, this study selected 15 major energy sources to estimate carbon dioxide emissions. These 15 energy sources are raw coal, washed coal, other washed coal, coke, coke oven gas, crude oil, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas, refinery dry gas, natural gas, heat, and electricity. The consumption of electricity and heat does not directly produce carbon dioxide, so an indirect calculation method is used to estimate the carbon dioxide emissions of electricity and heat in each year (Hu and Chen, 2023).

3.3.1.2 Explanatory variables

The game theory combined weighting method and the coupling coordination degree model are used to measure the coupling coordination level (GDDF) of green finance and digital technology. The specific measurement method is as described above.

3.3.1.3 Control variables

Based on previous studies (Zhou et al., 2023; Hu and Chen, 2023), this study further controls for other potential factors that may affect Air Pollution and Carbon Emissions. This study selects economic development level (perGDP), population size (pop), industrial structure (IS), green tax (Gret) and green fiscal expenditure (Gref) as control variables.

The economic development level is measured by the logarithm of GDP *per capita*, the population size is measured by the logarithm of the total population at the end of the year, and the industrial structure is measured by the ratio of the tertiary industry to the secondary industry.

This study uses the ratio of environmental protection expenditure to local fiscal expenditure to represent green fiscal expenditure, and uses the ratio of the sum of environmental protection tax and resource tax to local tax revenue to represent green tax. The environmental protection taxes used in this study mainly include urban construction and maintenance tax, urban land use tax, and cultivated land occupation tax (Hu and Chen, 2023; Zhu and Lu, 2017; Jiang, 2018).

3.3.1.4 Instrumental variables

Referring to previous studies (Li et al., 2023; Zhang et al., 2020), this study uses the distance of each province to Zhejiang Province as an instrumental variable. Zhejiang Province not only has a typical case of coordinated development of digital technology and finance represented by Alipay, but is also the birthplace of the "Two Mountains Theory" and the location of two major green financial reform and innovation pilot zones. Its level of coordinated development of green finance and digital technology is at the forefront of the country. Therefore, it can be expected that the closer the province is to Zhejiang Province geographically, the higher the degree of coordinated development of green finance and digital technology will be.

3.3.1.5 Mechanism variable

Based on previous studies (Xiong and Chen, 2022), green innovation (GI) was selected as a mechanism variable for further analysis. Green innovation is measured by the number of green patent authorizations.

3.3.2 Model

This study examines the impact of the joint use of green finance and digital technology on reducing pollution. To achieve this, a double fixed-effect econometric model is constructed, and a fixed-effect model is selected through the Hausman test.

$$lnperso_{2,it} = \beta_0 + \beta_1 GDDF_{it} + \beta_2 Contro_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (20)$$

$$lnperco_{2,it} = \alpha_0 + \alpha_1 GDDF_{it} + \alpha_2 Contro_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (21)$$

where:

$lnperso_{2,it}$ represents *per capita* sulfur dioxide emissions; $lnperco_{2,it}$ represents *per capita* carbon dioxide emissions; $GDDF_{it}$ points the level of coupling and coordination of green finance and digital technology; $Contro_{it}$ refers to a series of control variables; μ_i is province fixed effects; ν_t refers to time fixed effects, and

ε_{it} represents random disturbance terms.

In order to explore the transmission mechanism of the air pollution and carbon emission reduction effects of the coupling of green finance and digital technology, this study introduces green innovation (GI) to test the mechanism and constructs the following model based on existing research methods (Jiang and Luo, 2022).

$$lnGI_{it} = \gamma_0 + \gamma_1 GDDF_{it} + \gamma_2 Contro_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (22)$$

where:

$lnGI_{it}$ represents green innovation.

Other variables remain the same as in Formula 20.

4 Results

4.1 Indicator weighting results

This study utilized three different methods, subjective weighting, objective weighting, and game theory combined weighting, to

TABLE 5 Evaluation system for the coordinated development level of green finance and digital technology.

First-level indicators	Second-level indicators	Specific indicators	Subjective empowerment method	Objective weighting method	Game theory combination weighting method
Green Finance	Green Credit	Total interest expenses of the six major energy-consuming industries/Interest expenses	0.0911	0.05335	0.072225
	Green Securities	Market value ratio of environmental protection companies	0.1498	0.29843	0.224115
	Green Insurance	Scale environmental pollution insurance = agricultural insurance income/property insurance income	0.0744	0.23961	0.157005
		Environmental pollution insurance compensation ratio = agricultural insurance expenditure/agricultural insurance income	0.0744	0.05906	0.06673
	Green Investment	Proportion of investment in environmental governance = investment in environmental governance/GDP	0.1396	0.10111	0.120355
	Carbon Finance	Carbon emission loan intensity = RMB loan balance of financial institutions at the end of the year/carbon dioxide emissions	0.4707	0.24844	0.35957
Digital Technology	Digital Infrastructure	Total telecommunications business volume	0.5884	0.26453	0.426465
		Number of mobile phone users at the end of the year	0.269	0.26453	0.266765
		Number of Internet broadband access ports	0.0895	0.32553	0.207515
	Digital Technology Applications	Digital Inclusive Financial Development: China Digital Inclusive Financial Development Index	0.0531	0.14541	0.099255

calculate specific index weights for the evaluation index system. The results can be seen in Table 5.

The measurement results of the coordinated development level of green finance and digital technology in different provinces in China are shown in Table 6.

4.2 Analysis of dynamic evolution characteristics

In this study, we have utilized the Kernel Density Estimation method to investigate the dynamic evolution patterns of the coordinated development levels of green finance and digital technology coupling across various provinces in China during the given period. Furthermore, we have analyzed the dynamic evolution characteristics of the coordinated development level of green finance and digital technology coupling in eastern, central, western, and northeastern China, considering the regional heterogeneity. The figure below shows the results obtained from the Kernel Density Estimation.

The trends in the coupling and coordinated development levels of green finance and digital technology in different provinces in China are shown in Figure 1. The kernel density curve shows that from the distribution position, the center position of the curve moves to the right, indicating that the level of coordinated development of green finance and digital technology in China is on the rise. From the perspective of distribution pattern, the core density curve generally shows that the main peak height decreases and the amplitude width generally increases, indicating that the absolute gap in the coordinated development level of green finance and digital technology coupling in different provinces in China increased during the sample period. The kernel density curves of the coordinated development levels of green finance and digital technology in different provinces in China have an obvious right tail, indicating that the level of coupled and coordinated development of green finance and digital technology in one province is much greater than that of another province. The kernel density curves of the coordinated development levels of green finance and digital technology coupling in different provinces in China do not show an obvious bimodal distribution, indicating that there are no two poles in the coupling and coordinated development levels of green finance and digital technology in different provinces in China.

To analyze the evolving trend of the coupling and coordinated development of green finance and digital technology in different regions, Figure 2 displays the estimated results for the eastern region. The kernel density curve results are shown, and from the distribution position, it can be seen that the center position of

TABLE 6 Coupling and coordination degree of green finance and digital technology in different provinces in China.

Province	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Beijing	0.4659	0.5029	0.5379	0.5457	0.5476	0.5606	0.5687	0.5613	0.5532	0.5571
Tianjin	0.3482	0.3566	0.3630	0.3722	0.3673	0.3568	0.3752	0.3934	0.3942	0.4009
Hebei	0.3818	0.3940	0.4120	0.4056	0.4230	0.4254	0.4354	0.4389	0.4415	0.4637
Shanxi	0.3196	0.3368	0.3651	0.3561	0.3634	0.3779	0.3536	0.3615	0.3838	0.3746
Inner Mongolia Autonomous Region	0.3721	0.3882	0.4041	0.4063	0.4015	0.4008	0.4264	0.3967	0.3912	0.4250
Liaoning	0.3511	0.3846	0.3571	0.3999	0.4017	0.3702	0.3861	0.3845	0.3927	0.3993
Jilin	0.3275	0.3360	0.3381	0.3529	0.3631	0.3711	0.3800	0.3797	0.3737	0.3885
Heilongjiang	0.3500	0.3754	0.4164	0.4013	0.3991	0.4568	0.4117	0.4127	0.4264	0.4247
Shanghai	0.3197	0.3473	0.3460	0.3449	0.3438	0.3454	0.3670	0.3778	0.3899	0.3965
Jiangsu	0.3803	0.4031	0.4174	0.4314	0.4438	0.4559	0.4513	0.4770	0.4797	0.4885
Zhejiang	0.4144	0.4183	0.4624	0.4622	0.5012	0.5058	0.5150	0.5256	0.5355	0.5392
Anhui	0.3457	0.3553	0.3762	0.3690	0.3764	0.4096	0.3983	0.4073	0.4174	0.4538
Fujian	0.3576	0.3683	0.4133	0.4003	0.4212	0.4409	0.4279	0.4321	0.4391	0.4480
Jiangxi	0.3480	0.3657	0.3674	0.3687	0.3693	0.3823	0.3832	0.3990	0.4045	0.4152
Shandong	0.3722	0.4082	0.4242	0.3997	0.4145	0.4191	0.4510	0.4775	0.4829	0.4832
Henan	0.3427	0.3586	0.3900	0.3942	0.3929	0.4173	0.4387	0.4321	0.4439	0.4482
Hubei	0.3841	0.4016	0.4207	0.4160	0.4076	0.4276	0.4168	0.4258	0.4204	0.4155
Hunan	0.3690	0.3820	0.4025	0.3945	0.4092	0.4010	0.4106	0.4211	0.4380	0.4496
Guangdong	0.4860	0.5197	0.5541	0.5605	0.5860	0.5851	0.5895	0.6104	0.5974	0.5916
Guangxi Zhuang Autonomous Region	0.3367	0.3506	0.3517	0.3720	0.3978	0.3914	0.3942	0.4190	0.4487	0.4607
Hainan	0.3079	0.3010	0.3006	0.3356	0.3288	0.3542	0.3639	0.3797	0.3921	0.4134
Chongqing	0.3907	0.3907	0.4142	0.4155	0.4107	0.4099	0.4179	0.4350	0.4454	0.4390
Sichuan	0.3820	0.3869	0.4311	0.4414	0.4453	0.4517	0.4611	0.4730	0.4982	0.4895
Guizhou	0.3293	0.3484	0.3411	0.3546	0.3622	0.3637	0.3804	0.4062	0.4156	0.4215
Yunnan	0.3705	0.3922	0.4102	0.4153	0.4126	0.4174	0.4174	0.4347	0.4328	0.4359
Shaanxi	0.3315	0.3658	0.3523	0.3597	0.3777	0.3860	0.3915	0.3995	0.4042	0.4188
Gansu	0.3477	0.4015	0.3981	0.3954	0.4051	0.4060	0.4040	0.4564	0.4240	0.4203
Qinghai	0.3126	0.4321	0.3576	0.3555	0.3672	0.3790	0.3769	0.3757	0.3839	0.3845
Ningxia Hui Autonomous Region	0.3324	0.3940	0.3527	0.3588	0.3625	0.3748	0.3620	0.3639	0.3692	0.3700
Xinjiang Uygur Autonomous Region	0.3170	0.4052	0.3654	0.3747	0.3638	0.3692	0.3760	0.3731	0.3444	0.3763

the curve generally moves towards the right, indicating an increase in the level of coordinated development of green finance and digital technology in the eastern region. The kernel density curve generally shows that the main peak height is decreasing, and the amplitude width is slightly widening. This suggests that the absolute gap in the coordinated development level of green finance and digital technology coupling in the eastern region has slightly increased during the sample period.

From the perspective of distribution extensibility, the kernel density curve of the coordinated development level of green finance and digital technology coupling in the eastern region has a noticeable right tail. This means that the level of coupled coordinated development of green finance and digital technology is much higher in one province than in another within the eastern region. Furthermore, there is no obvious bimodal distribution in the coordinated development level of green finance and digital technology coupling in the eastern region, which indicates that there is no polarization phenomenon.

The results of the estimation for the central region are displayed in Figure 3. The kernel density curve results are depicted in the figure. The position of the curve's center generally moves to the right, indicating that the level of coordinated development between green finance and digital technology in the central region is on the rise. The kernel density curve generally shows that the main peak

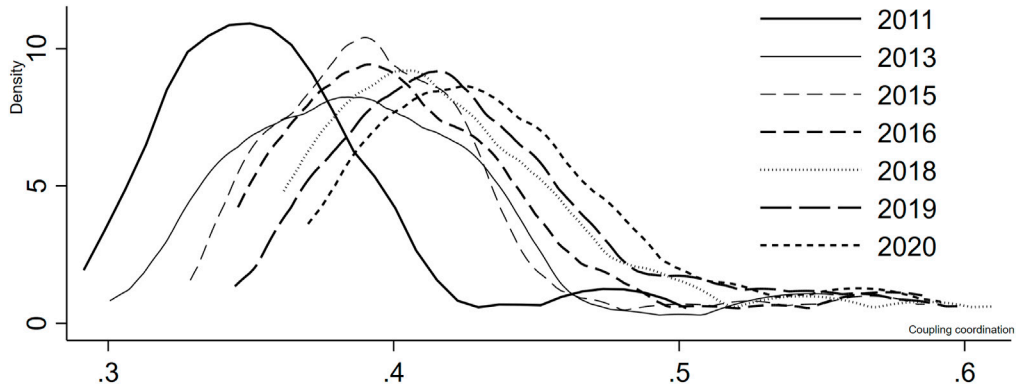


FIGURE 1
Estimation results of the nationwide sample Kernel density.

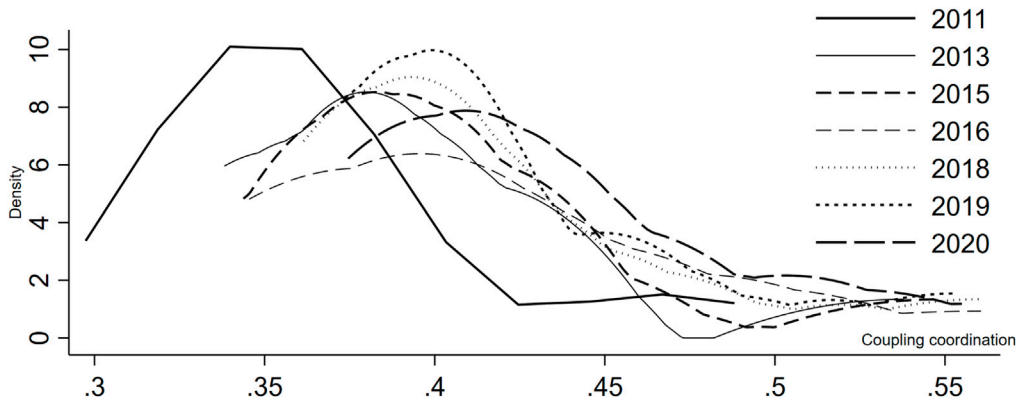


FIGURE 2
Estimation results of Kernel density in the eastern region.

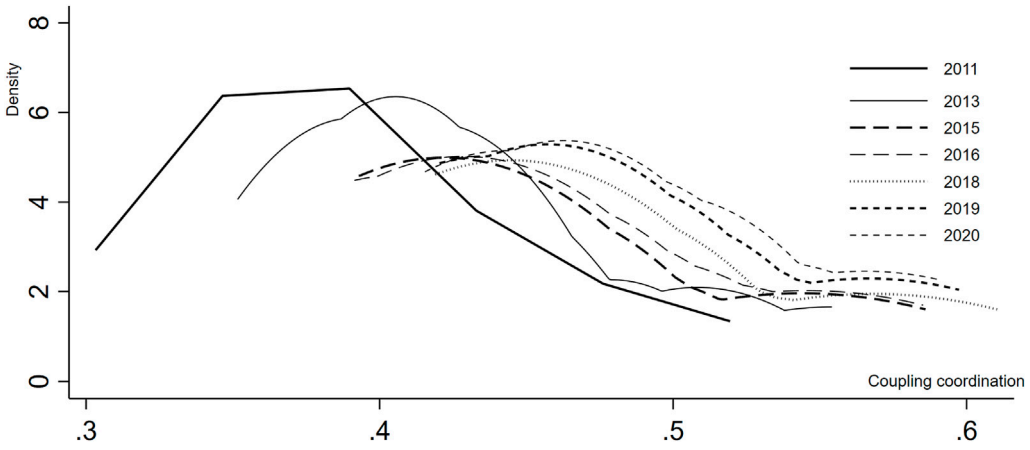


FIGURE 3
In the central Kernel nuclear density estimation result.

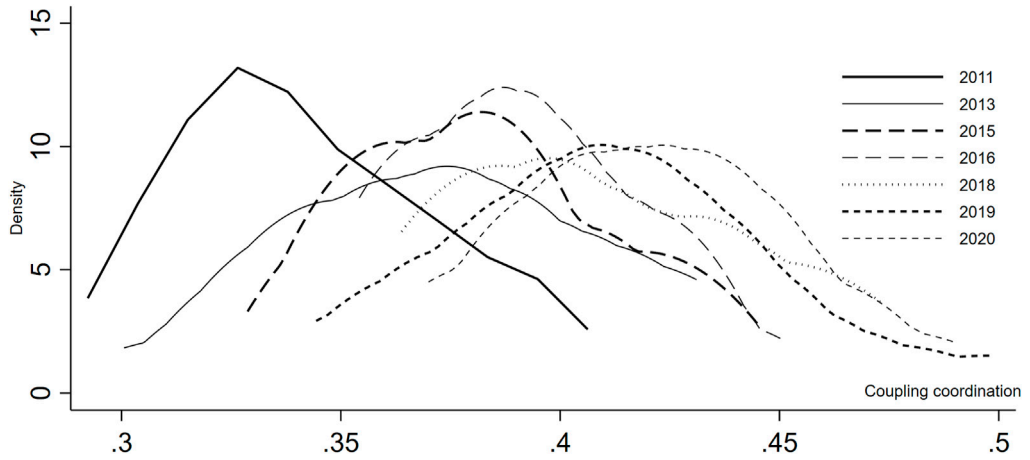


FIGURE 4
Estimation results of Kernel density in the western region.

height is decreasing, and the amplitude width is slightly widening, indicating that the absolute disparity in the level of coordinated development between green finance and digital technology coupling in the central region has slightly increased during the sample period. The kernel density curve of the coordinated development level of green finance and digital technology coupling in the central region has a significant right tail, suggesting that the level of coupling and coordinated development of green finance and digital technology in one province is much higher than that in another province. The kernel density curve of the level of coupled and coordinated development of green finance and digital technology in the central region does not exhibit an obvious bimodal distribution, indicating that there is no significant polarization phenomenon in the level of coupled and coordinated development of green finance and digital technology in the central region.

The results of the estimation for the western region are presented in Figure 4. The results are represented in the form of a kernel density curve. Looking at the distribution position, we can observe that the center position of the curve generally moves to the right, indicating a rise in the level of coordinated development of green finance and digital technology in the western region. Considering the distribution shape, we can see that the height of the main peak shows a downward trend, and the amplitude width widens slightly. This suggests that the absolute gap in the coordinated development level of green finance and digital technology coupling in the western region has slightly increased during the sample period. From the perspective of distribution extensibility, the kernel density curve of the coordinated development level of green finance and digital technology coupling in the western region does not show a significant right tailing phenomenon. This indicates that no province in the western region has a much better level of coordinated development of green finance and digital technology than others. Lastly, the kernel density curve of the coordinated development level of green finance and digital technology in the western region does not show a bimodal distribution, which suggests that there is no significant polarization phenomenon in the coordinated development level of green finance and digital technology in the western region.

The results of the estimation for the Northeast region are presented in Figure 5, which displays the kernel density curve outcomes. From the perspective of the distribution position, the center position of the curve generally moves to the right, indicating that the level of coordinated development of green finance and digital technology coupling in Northeast China is generally increasing. From the distribution pattern viewpoint, the kernel density curve generally shows a downward trend in the main peak height, and the amplitude width generally widens slightly, indicating that the absolute gap in the level of coordinated development of green finance and digital technology coupling in Northeast China has slightly increased during the sample period. Regarding distributed ductility, the kernel density curve of the coordinated development level of green finance and digital technology in the Northeast doesn't have any apparent right-tail phenomenon, indicating a relatively uniform distribution between the provinces in the Northeast region. Similarly, there isn't any obvious double-peak distribution in the kernel density curve of the coordinated development level of green finance and digital technology in the Northeast, which demonstrates that there is no visible phenomenon of bipolar differentiation in the coordinated development level of green finance and digital technology coupling in the Northeast region.

To summarize, the coordination between green finance and digital technology has increased in the national average, east, central, west, and northeast regions of the country. However, there is a significant gap between these regions. One province stands out as having a much higher level of coordination compared to the national average, as well as the eastern and central regions. This phenomenon is not observed in the western and northeast regions. There is no clear evidence of bipolar differentiation in the coordinated development level of green finance and digital technology coupling across different regions.

4.3 Forecast of long-term evolution trend based on traditional Markov chain model

The Kernel density curve shows the overall form and dynamic evolution of the level distribution of this coupling, but does not

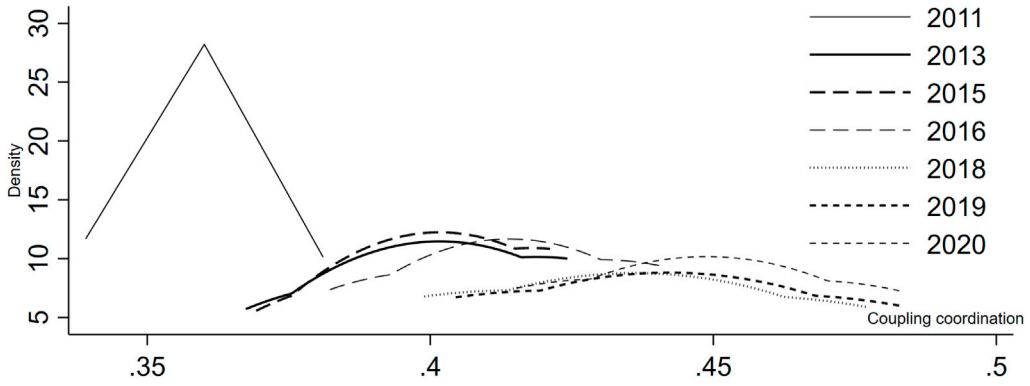


FIGURE 5
Estimation results of nuclear density in Northeast China.

TABLE 7 Coupling coordination level Traditional Markov chain the model transfer probability matrix.

t/t+1	I	II	III	IV
I	0.6164	0.3151	0.0548	0.0137
II	0.1618	0.5147	0.3088	0.0147
III	0.0714	0.1143	0.6429	0.1714
IV	0.1159	0.0290	0.0580	0.7971

reflect its long-term evolution trend. To predict this trend, the study uses a traditional Markov chain model. Firstly, the coordinated development level of green finance and digital technology is classified into four levels using the quadrilateral bias method. Then, the Markov chain transfer probability matrix of Chinese green finance and digital technology coupling coordination is calculated. The results are presented in Table 7.

The results shown in Table 7 indicate that 61.64% of provinces have remained at a low-level year after year. 31.51% of provinces have moved from low to low-medium levels annually. The probability of a province moving to the medium-high level and high levels of coordinated development between green finance and digital technology is 5.48% and 1.37%, respectively. One year later, 51.47% of provinces maintain their unchanged low-medium level of coordinated development between green finance and digital technology. The probability of a province moving to the medium-high level of coordinated development is 30.88%. The probability of transitioning to a high level of coordinated development between green finance and digital technology is 1.47%, while 16.18% of provinces move to a low level. One year later, 64.29% of provinces still maintain their medium-high level of coordinated development between green finance and digital technology. 17.14% of provinces will move from their current level to a higher level of coordinated development. The probability of moving from the current level to the low-medium level of coordinated development between green finance and digital technology is 11.43%, and the probability of moving to a low level is 7.14%. After a year, 79.71% of provinces will still maintain their high level of coordinated development between green finance and digital technology. The probability of moving to the medium-high level of coordinated development between green finance and digital technology is 5.8%. The probability of moving down to a low-medium level and low-level of coordinated development between green finance and digital technology is 2.9% and 11.59%, respectively.

Based on the analysis results, it can be observed that in the Markov metastasis probability matrix, the probability of metastasis on the diagonal line is higher than the probability on the non-diagonal line. This indicates that when the probability of maintaining the original level is higher than the probability of transfer, the club with this level will converge. Thus, there is a clear phenomenon of "club convergence" in the coordinated development level of green finance and digital technology coupling. The convergence is more significant in medium-high and high levels, with probabilities of 64.29% and 79.71%, respectively. On the other hand, the probability of low-medium and low levels is less, with probabilities of 51.47% and 61.64%, respectively. This means that the probability of maintaining a stable development level of Chinese green finance and digital technology coupling is at least 51.47%. Additionally, it indicates that there is a "Matthew effect" of the rich and poor in the coordinated development level of Chinese green finance and digital technology coupling.

4.4 Long-term evolution trend forecast based on space Markov chain model

In order to keep up with the evolving trends in the coordinated development of Chinese green finance and digital technology, the Space Markov Chain has been adopted to analyze the impact of spatial factors on this development. The traditional Markov chain alone is not sufficient in reflecting the spatial overflow. To overcome this limitation, a spatial Markov transfer probability matrix has been built by adding space lag conditions to the traditional transfer probability matrix. By comparing the probability of coordinated development levels in different neighborhoods, we can analyze the impact of neighborhood backgrounds on the development of green finance and digital technology.

TABLE 8 Coupled coordination horizontal space Markov transition probability matrix.

Domain type	t/t+1	I	II	III	IV
k = 1	I	0.6226	0.3019	0.0566	0.0189
	II	0.2258	0.5484	0.1935	0.0323
	III	0.0385	0.0769	0.7308	0.1538
	IV	0.0589	0	0.0588	0.8824
k = 2	I	0.5	0.5	0	0
	II	0	0.5333	0.4	0.0667
	III	0	0	0.8	0.2
	IV	0	0	0	1
k = 3	I	0.8	0.2	0	0
	II	0	0.5	0.5	0
	III	0	0	0.6	0.4
	IV	0	0	0.3333	0.6667
k = 4	I	0.5385	0.3846	0.0769	0
	II	0.0435	0.4348	0.4783	0.0435
	III	0	0.1333	0.6667	0.2000
	IV	0	0	0.0278	0.9722

Table 8 reflects the spatial Markov chain transition probability of the coupling and coordinated development level of green finance and digital technology. The data shows that when the neighboring provinces are at a low level (k = 1), the probability of low-level provinces in the region remaining at the original level is 62.26%, and the probability of moving upward to the medium-low level is 30.19%. The probability of positive jump transfer to medium-high and high levels is 5.66% and 1.89% respectively. The probability that provinces with low-to-medium levels in this region will remain at the original level is 54.84%. The probability of upward transfer to medium-high levels is 19.35%, the probability of forward jump transfer to a high level is 3.23%, and the probability of downward transfer to a low level is 22.58%. The probability that provinces in this region are medium-high levels will remain at the original level is 73.08%, the probability of moving upward to a high level is 15.38%, the probability of moving downward to a medium-low level is 7.69%, and the probability of a negative jump to a low level is 3.85%. The probability that high-level provinces will remain at their original levels is 88.24%. The probability of downward transfer to medium-high levels is 5.88%, and the probability of negative jump transfer to medium-low and low levels is 0% and 5.89% respectively.

When the neighboring provinces are at medium-low level (k = 2), the probability of low-level provinces in the region remaining at the original level is 50%. The probability of upward transfer to medium-low levels is 50%, and the probability of forward jump transfer to medium-high levels is 0%. The probability that provinces with low-medium levels in this region will remain at the original level is 53.33%. The probability of upward transfer to medium-high levels is 40%, the probability of forward jump transfer to a high level is 6.67%, and the probability of downward transfer to a low level is 0%. Provinces with medium-high levels in this region have an 80% probability of remaining at the original level. The probability of upward transfer to a high level is 20%, the probability of downward transfer to a medium-low level is 0%, and the probability of negative jump transfer to a low level is also 0%. The probability of a high-level province remaining at the original level is 100%, the probability of moving downward to a medium-high level is 0%, and the probability of a negative jump to a medium-low level or low level is also 0%.

When the neighboring provinces are at medium and high levels (k = 3), the probability of low-level provinces in the region maintaining their original levels is 80%, the probability of moving upward to medium-low levels is 20%, and the probability of forward jumps to medium-high level and high level are both 0%. The probability of low-medium level provinces in this region maintaining the original level is 50%, the probability of moving upward to a medium-high level is 50%, and the probability of moving downward to a low level and jumping to a high level is 0%. The probability that provinces with medium-high levels in this region will maintain their original level is 60%, the probability of moving upward to a high level is 40%, and the probability of moving downward to a medium-low level and making a negative jump to a low level are both 0%. The probability of high-level provinces in this region maintaining the original level is 66.67%, the probability of moving downward to a medium-high level is 33.33%, and the probability of negative jump transfer is 0%.

When the neighboring provinces are at a high level (k = 4), the probability that the low-level provinces in the region remain at the original level is 53.85%. The probability of upward transfer to the middle-low level is 38.46%, the probability of forward jump transfer to the middle-high level is 7.69%, and the probability of high level is 0% respectively. The probability of provinces with medium-low levels in this region remaining at the original level is 43.48%, and the probability of moving upward to a medium-high level is 47.83%. The probability of a positive jump to a high level is 4.35%, and the probability of a downward jump to a low level is also 4.35%. The probability of provinces with medium-high levels in this region remaining at the original level is 66.67%. The probability of upward transfer to a high level is 20%, the probability of downward transfer to a medium-low level is 13.33%, and the probability of negative jump transfer to a low level is 0%. The probability of a high-level province remaining at the original level is 97.22%, the probability of moving downward to a medium-high level is 2.78%, and the probability of a negative jump to a medium-low level and low level is both 0%.

By comparing Tables 7, 8, the following conclusions can be drawn. First, the four transition probability matrices under the four spatial lag conditions are all different. It shows that when neighboring provinces have different levels of coupled and coordinated development of green finance and digital technology, the probabilities of being affected and transferred vary, and there is a certain degree of spatial and geographical dependence. Second, spatial factors have a significant impact on the dynamic transfer of the coordinated development level of green finance and digital technology. Third, the evolution of development types is unstable. In the four transition probability matrices in Table 8, the lower triangle area is not all 0, indicating that even if it is in a better development type in year *t*, it may still shift downward to a lower development type in year *t* + *1*. In particular, the medium-low level and the

TABLE 9 Summary statistics.

Variables	Obs	Mean	Median	SD	Min	Max
GDDF	300	0.408	0.399	0.057	0.301	0.610
perCO2	300	13.087	7.338	17.033	1.053	80.850
perSO2	300	0.010	0.005	0.012	0.001	0.064
perGDP	300	5.369	4.635	2.695	1.591	16.420
IS	300	1.324	1.171	0.729	0.527	5.244
Gref	300	0.030	0.028	0.010	0.012	0.068
Gret	300	0.163	0.162	0.062	0.050	0.419
pop	300	4,599.783	3,917.500	2,837.845	568.000	13,000.000

medium-high level are most susceptible to transformation, indicating that the level of coordinated and coordinated development of green finance and digital technology is still unstable. Fourth, the level of coupled and coordinated development of green finance and digital technology in a province has an important impact on the future coupled and coordinated development of green finance and digital technology. Being adjacent to medium-high-level provinces, the probability of low-level development upward is only 20%, but the probability of medium-low level turning to high-level is 50%, which is a significant change. This shows that areas with higher levels of their own are more likely to move to higher levels. Fifth, there is an obvious club convergence phenomenon in the coupling and coordinated development of green finance and digital technology. The phenomenon of high-level convergence and low-level convergence is more significant, that is, the probability of maintaining stability in low-level and high-level areas on the diagonal are all relatively high, which also verifies the "Matthew Effect" existing in the coordinated development level of green finance and digital technology in the previous analysis.

5 Analysis of pollution reduction and emission reduction effects

5.1 Descriptive statistics

This study focuses on 30 provinces, autonomous regions, and municipalities in China, from 2011 to 2020. Tibet, Hong Kong, Macao, and Taiwan are not included due to missing data. To ensure accuracy, the data has been winsorized at the 5% level. Descriptive statistics for each variable can be found in Table 9.

5.2 Empirical test

5.2.1 Baseline regression

Table 10 reports the baseline regression results of the pollution emission effects of the coupling and coordination level of green finance and digital technology. The results of regression (1) show that, based on controlling for time and province, the coefficient of GDDF is significant at the 1% level, indicating that the coupled and coordinated development of green finance and digital technology has a significant air pollution reduction effect. The results of regression (2) show that the coefficient of GDDF is significant at the 5% level, indicating that the coupled and coordinated development of green finance and digital technology has a significant carbon emission reduction effect. Hypothesis 1 is verified. This shows that the coupling of green finance and digital technology has a significant emission reduction effect. Since the development of green finance has certain environmental restrictions, digital technology can provide a paperless platform for the development of green finance, realize the dissemination and sharing of lending information, break the barriers of information dissemination, achieve green economic development, and then promote global sustainable development.

An analysis of the control variables found that the level of economic development (perGDP) has a certain inhibitory effect on pollution reduction and emission reduction, and has a significant impact on reducing air pollution, but has an insignificant impact on carbon dioxide emission reduction. The impact of industrial structure (IS) on pollution reduction and emission reduction is not significant. Green tax policy (Gret) has a certain inhibitory effect on pollution reduction and emission reduction, and has a significant impact on reducing air pollution, but has an insignificant effect on carbon dioxide emission reduction. Green fiscal expenditure (Gref) has a significant promoting effect on reducing air pollution, but has an insignificant inhibitory effect on carbon dioxide emission reduction. Population will increase air pollution and carbon dioxide emissions, and will have a significant impact on increasing carbon dioxide.

5.2.2 Robustness analysis

First, the original data before winnowing are used for robustness testing. The results are shown in regressions (1) and (2) of Table 11. Secondly, the explained variables are replaced for robustness testing. The logarithm of total SO2 emissions and total CO2 emissions was used to conduct robustness testing, and the results are shown in regressions (3) and (4) in Table 11.

Table 11 shows that after using the original data and replacing the explained variables, the regression results of the pollution emission reduction effects of the coupled and coordinated development of green finance and digital technology are still significant. The estimation results are consistent with the

TABLE 10 Baseline regression results.

Variables	(1)	(2)
	lnperSO2	lnperCO2
GDDF	−4.632***	−2.594**
	(−3.60)	(−2.18)
perGDP	−0.096*	−0.008
	(−1.90)	(−0.16)
IS	0.213	−0.184
	(1.18)	(−1.10)
Gret	−2.011**	−1.091
	(−1.99)	(−1.16)
Gref	9.203**	−3.754
	(2.21)	(−0.97)
pop	0.384	1.512*
	(0.42)	(1.80)
Constant	−6.087	−8.754
	(−0.83)	(−1.30)
Observations	300	300
R-squared	0.916	0.920
prov	Y	Y
Year	Y	Y
r2_a	0.901	0.906

Note: The values in parentheses are t. ***, ** and * indicate significance at the 1%, 5% and 10% levels respectively. "Y" indicates fixed effects.

previous baseline regression results. It further proves that the coupled and coordinated development of green finance and digital technology has significant pollution emission reduction effects.

5.2.3 Endogeneity analysis

Endogeneity problems may still exist when conducting robustness tests by replacing the explained variables. Therefore, this study draws on the practices of previous scholars (Li et al., 2023; Zhang et al., 2020) and selects the product of the distance from each province to Zhejiang Province and the average value of the coordinated development of green finance and digital technology in other regions except this province as the instrumental variable to conduct endogeneity testing. Because Zhejiang Province not only has typical cases of coordinated development of digital technology and finance represented by Alipay, but is also the birthplace of the "Two Mountains Theory" and the location of two major green financial reform and innovation pilot zones. Its level of coordinated development of green finance and digital technology is at the forefront of the country. Therefore, it can be expected that the closer the geographical distance to Zhejiang Province, the higher the level of coordinated development of green finance and digital technology will be.

The results are displayed in Table 12, where Regression (1) and (2) present the regression outcomes of the second stage. The coefficients before GDDF are all positive, indicating that the coordinated development of green finance and digital technology still has a significant pollution emission reduction effect after taking potential endogeneity issues into account. This result is consistent with the baseline regression conclusion. It shows that the coupled and coordinated development of green finance and digital technology can achieve the goal of pollution emission reduction.

5.3 Further analysis: mechanism testing

The above-mentioned research shows that the coupled development of green finance and digital technology can produce significant pollution emission reduction effects, which is of great significance to the realization of China's "double carbon" goal and global sustainable development under the new development pattern. Then, what needs to be further explored is how the coupling of green finance and digital technology can help achieve pollution emission reduction goals.

Based on the theoretical mechanism analysis, this study introduces green innovation (GI) to explore the transmission

TABLE 11 Robustness test.

Variables	(1)	(2)	(3)	(4)
	lnperSO2	lnperCO2	lnSO2	lnCO2
GDDF	−3.446***	−2.097*	−4.515***	−2.748**
	(−2.84)	(−1.73)	(−3.68)	(−2.31)
perGDP	−0.014	0.045	−0.114**	−0.006
	(−0.40)	(1.27)	(−2.36)	(−0.124)
IS	0.845***	0.066	0.058	−0.185
	(5.57)	(0.43)	(0.34)	(−1.108)
Gret	−1.504*	−0.537	−1.763*	−0.997
	(−1.96)	(−0.70)	(−1.83)	(−1.065)
Gref	3.274	−3.090	9.184**	−3.969
	(0.99)	(−0.93)	(2.31)	(−1.029)
pop	0.457	0.943	1.061	2.604***
	(0.56)	(1.15)	(1.23)	(3.110)
Constant	−8.343	−4.990	−3.221	−0.250
	(−1.26)	(−0.75)	(−0.46)	(−0.04)
Observations	300	300	300	300
R-squared	0.922	0.919	0.886	0.853
prov	Y	Y	Y	Y
Year	Y	Y	Y	Y
r2_a	0.909	0.905	0.866	0.827

Note: The values in parentheses are t. ***, ** and * indicate significance at the 1%, 5% and 10% levels respectively. "Y" indicates fixed effects.

mechanism of green finance and digital technology coupling coordination to reduce air pollution and carbon emissions. Drawing on the existing research methods (Jiang and Luo, 2022), the relationship between each mediating variable and the dependent variable is first determined through theoretical analysis, and then the impact of the coupling coordination level of green finance and digital technology on the mediating variable is empirically tested. Table 13 reports the mechanism test based on green innovation. The regression results show that the coefficient of coupling and coordination level of green finance and digital technology is significantly positive, indicating that the coordinated development of green finance and digital technology has a significant promotion effect on green innovation. The coupling and coordination of green finance and digital technology achieve pollution emission reduction by driving green innovation. Hypothesis 2 is verified. This is similar to the conclusion drawn by Li et al. (2023).

The control variable results show that the coefficient of economic development level (perGDP) is 0.321, which is significantly positive at the 1% level, indicating that the level of economic development has a significant promoting effect on green innovation. The coefficients of industrial structure and green tax policy are both positive and insignificant, indicating that their impact on green innovation is not significant. The coefficient of green tax policy is −2.388, which is significant at the 1% level, indicating that green tax policy has a significant promotion effect on green innovation. The coefficient of population size is 1.139, which is significant at the 1% level, indicating that population size has a significant promotion effect on green innovation.

6 Discussion

First, this study found that the level of green finance and digital technology coupling coordination in the entire sample of Chinese provinces, provinces in the eastern region, provinces in the central region, provinces in the western region, and provinces in the northeast region showed an upward trend, and there were differences in different regions, which is similar to the trend of studying the single status of green finance (Xu and Jiang, 2021)and digital finance (Sui and Xu, 2024). Compared with other studies, this study newly found that there is an obvious club convergence phenomenon in the level of green finance and digital technology coupling coordination development, and there is a "Matthew effect." This is due to the imbalance of regional development in China (Xing and He, 2024) and resource mismatch (Lu and Lu, 2024).

Second, this study mainly analyzes the pollution reduction and emission reduction effects brought about by the coupled and

TABLE 12 Instrumental variable test.

Variables	(1)	(2)
	lnperSO2	lnperCO2
GDDF	−2.784***	−5.077***
	(−4.690)	(−5.87)
perGDP	0.066***	0.052***
	(3.493)	(3.391)
IS	−0.426***	0.460***
	(−4.533)	(6.809)
Gret	10.212***	15.438***
	(4.090)	(4.229)
Gref	2.357***	0.996*
	(3.776)	(1.694)
Observations	300	300
Kleibergen-Paap F statistic	57.70	75.917
prov	Y	Y
Year	Y	Y

Note: The values in parentheses are t. ***, ** and * indicate significance at the 1%, 5% and 10% levels respectively. "Y" indicates fixed effects.

coordinated development of digital technology and green finance. Similar conclusions to previous studies show that digital finance or green finance has a significant effect on reducing pollution and emissions. Digital finance connects the business systems of financial institutions with the underlying data platform of the green information system, shortens the time for financial institutions to identify green projects, simplifies the approval and issuance process of green loans, and improves the efficiency of financial services. Secondly, digital finance is mainly based on online virtual outlets. With the help of business models such as Internet banking, it relies on massive customer resources and digital technology to form strong network externalities, conduct contactless transactions, reduce the energy consumption of cash, paper, and rides during transactions, and promote green development. Green development plays a key role in achieving pollution reduction and emission reduction goals. This approach can reduce the moral hazard caused by information asymmetry and enable enterprises to more smoothly use green finance to reduce pollution and control emissions (Zhao et al., 2024b; Wang et al., 2024b; Wang et al., 2024b; Magazzino et al., 2023). In addition, the coupled and coordinated development of green finance and digital technology can exacerbate financing constraints for the progress and development of ecological pollution-related enterprises. However, existing research only considers the carbon emission reduction effect of a single aspect of green finance or digital finance (Xie and Liu, 2019; Guo et al., 2022; Mao and Wang, 2023; Ran and Zhang, 2023). This study examines the pollution reduction effect of the coupled and coordinated development of the two. Empirical results show that after controlling for population, economic development level, industrial structure development level, green tax policy and green fiscal policy, the coupled and coordinated development of green finance and digital technology has a significant pollution reduction effect.

The main reason for this result is that the improvement of digital transformation construction enables the government to efficiently and accurately obtain carbon emission-related data and formulate timely response measures (Alam and Murad, 2020). Secondly, compared with green enterprises, the coordinated development of green finance and digital technology breaks the barriers to the penetration of green finance and green benefit information, improves the ability to process and identify green financial information, and effectively drives green technology innovation in polluting enterprises (Li et al., 2023). Finally, by utilizing the digital infrastructure effect to improve the coverage and efficiency of green financial services, and using infrastructure such as information and communication technology to improve energy efficiency through a shared resource network, urban carbon emissions can be reduced and green development can be promoted (Anser et al., 2021; Lange et al., 2020).

Third, Schumpeter's innovation theory suggests that financial development has a strong supporting role in innovation (Aghion et al., 2012). Since green innovation has the characteristics of sunk investment, uncertainty of results and high adjustment costs, it is difficult to meet the funds required for innovation by relying solely on internal corporate funds and national R&D expenditures. Therefore, external financing is the key to promoting technological innovation. The development of digital finance makes up for the mismatch of attributes, fields and stages in traditional financial services, improves the efficiency of capital allocation, and can effectively support corporate green technology innovation and enable green development. On the one hand, digital finance has lowered the threshold and cost of financial services,

TABLE 13 Mechanism test.

Variables	GI
GDDF	1.623**
	(2.471)
perGDP	0.321***
	(21.011)
IS	−0.050
	(-0.726)
Gret	−2.388***
	(−3.931)
Gref	0.891
	(0.297)
pop	1.139***
	(25.802)
Constant	−3.594***
	(−8.741)
Observations	300
prov	Y
Year	Y
r2_a	0.984

Note: The values in parentheses are t. ***, ** and * indicate significance at the 1%, 5% and 10% levels respectively. "Y" indicates fixed effects.

increased the availability of financial resources, and can provide more targeted financial support for corporate R&D and innovation (Nie et al., 2021), thereby improving the utilization rate of financial resources, accelerating the flow of innovation capital, and increasing the number of green technology innovation results (Tang et al., 2020). On the other hand, digital finance uses digital technology to search, analyze and make decisions on consumer preference information for green products. It helps enterprises determine the direction and path of green innovation, promotes the transformation of enterprise innovation from experience-driven to data-driven (Liu et al., 2020b), realizes effective green technology R&D decision-making, and improves the quality of green technology innovation. Secondly, the improvement of green technology innovation capabilities has the effect of energy conservation and emission reduction, and promotes green development. On the one hand, enterprises with strong green technology innovation improve energy utilization and reduce energy consumption by developing new or improving existing technologies. On the other hand, enterprises penetrate green technology into all aspects of production, break the path dependence of the development of polluting industries, guide enterprises to save energy and reduce emissions, reduce pollutant emissions based on production output, and are conducive to green development (Mao and Wang, 2023). This study examines the mechanism of green innovation in the coordinated development of green finance and digital technology on pollution reduction and emission reduction. The results show that the coordinated development of green finance and digital technology achieves pollution reduction and emission reduction through green innovation. This is similar to the conclusion of the previous study.

This result is mainly due to the fact that digital technology can enhance the financing capacity of enterprises by breaking down the information barriers of green finance, providing digital platforms and innovative service support measures, thereby increasing investment in research and development. This in turn promotes technological innovation in enterprises and promotes the adoption of green technologies, thereby promoting innovation and directly achieving pollution reduction through the coordinated development of green finance and digital technology. In addition, technological innovation reduces carbon emissions by promoting the development of the renewable energy industry and reducing energy intensity (Han and Gu, 2021; Cheng et al., 2021b; Yao and Yang, 2022), and this phenomenon also exists in some countries (Miśkiewicz, 2021; Ullah et al., 2021).

Finally, this study provides a model and ideas for developing countries to analyze the current level of coordinated development of green finance and digital technology. It provides a new policy-making path for achieving the coordinated development of green finance and digital technology in China at this stage. It is of great significance to the green transformation of the economy and high-quality development, and also provides empirical evidence and reference for other developing countries to achieve the coordinated development of green finance and digital technology and promote pollution reduction and emission reduction.

7 Conclusion and outlook

7.1 Conclusion

This study employs the game theory combination weighting method to evaluate the degree of coordinated development between green finance and digital technology in China. It uses Kernel density estimation, traditional Markov chain model, and spatial Markov chain model to analyze the dynamic evolution characteristics and trends, and also examines the pollution reduction effect of the coordinated development of green finance and digital technology through empirical testing. The key findings of this study are as follows.

First, the level of coupling and coordination between green finance and digital technology is increasing in all Chinese provinces, including the eastern, central, western, and northeastern regions. However, there is a noticeable difference in the level of coordinated development between different provinces, particularly in the eastern and central regions. This difference is not as pronounced in the western and northeastern regions. Overall, there is no significant polarization in the level of coupling and coordinated development of green finance and digital technology across all regions.

Second, The traditional Markov transition probability matrix results of China's green finance and digital technology coupling and coordinated development level show that there is an obvious "club convergence" phenomenon. This shows that there is a "Matthew effect" in which the rich get richer and the poor get poorer in China's coupled and coordinated development of green finance and digital

technology. Spatial factors are further introduced and the spatial Markov chain model is used for research. The results show that spatial factors have a significant impact on the dynamic transfer of the coordinated development level of green finance and digital technology, and the evolution of development types is unstable. The level of provincial green finance and digital technology coupling and coordinated development has an important impact on the future green finance and digital technology coupling and coordinated development. The results show that regions with higher levels are more likely to move to higher levels.

Third, through empirical testing, it is found that the coupled and coordinated development of green finance and digital technology has significant pollution emission reduction effects. Further mechanism testing of the pollution emission reduction effects of the coupling of green finance and digital technology showed that the coupling of green finance and digital technology achieves pollution emission reduction by driving green innovation.

7.2 Recommendations and outlook

First, we should continue to enhance and develop green finance, encourage the use of digital technology, and promote the optimization of industrial structures. Currently, the focus of domestic green finance is mainly on green credit, which makes it challenging to meet the financing requirements of different levels, terms, and natures. There is an urgent need for rich green financial products, convenient investment and financing processes, and scientific and reasonable financial supervision to support industrial transformation and structural optimization. In addition, none of the published green finance policy documents reflects attitudes towards greenhouse gases such as carbon dioxide, making governance less precise. If greenhouse gas emission indicators such as carbon dioxide can be included in the financing conditions of green financial products and paperless product transactions can be implemented, it will be more conducive to promoting pollution reduction and carbon reduction.

Second, we can adjust the green tax rate and scale. Resource tax and environmental protection tax rates are low, which is not conducive to environmental governance. Pilot work can be carried out in areas with a low proportion of green taxes and good economic development levels, appropriately increase the tax rates on taxable resources and pollutants, increase green tax revenue, and adjust the scale of green taxation to a reasonable range. At the same time, green fiscal policies such as tax incentives and financial subsidies for new energy, renewable energy, and industrial structure optimization will be adopted.

Third, we can optimize green fiscal spending. The scope of environmental protection expenditures is limited to pollution control, environmental management, and monitoring, and there is a lack of supervision and management of greenhouse gases such as carbon dioxide. Therefore, adjusting the scope of environmental protection expenditures, paying more attention to carbon emissions, and releasing policy signals and determination to intervene will promote green finance to better exert its effects on pollution reduction and carbon reduction.

Fourth, we can build and optimize a digital green financial product trading platform, provide a paperless business processing platform, and implement platform supervision to achieve pollution reduction and emission reduction effects.

This study examines the current characteristics and pollution reduction effects of the coordinated development of green finance and digital technology in China, in light of the progress of society and the rapid growth of the economy and the Internet. However, there are also some shortcomings in the writing process of this article, which need to be further studied in the future. The impact pathway of the coordinated development of green finance and digital technology has not been specifically analyzed, and there is still room for discussion. Due to limited time, this article did not delve deeper into this aspect, which needs to be further explored in subsequent research.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

KL: Funding acquisition, Methodology, Writing–original draft. RD: Software, Writing–original draft. BX: Software, Resources, Data curation, Writing–review and editing. JH: Resources, Conceptualization, Writing–review and editing. ZW: Conceptualization, Resources, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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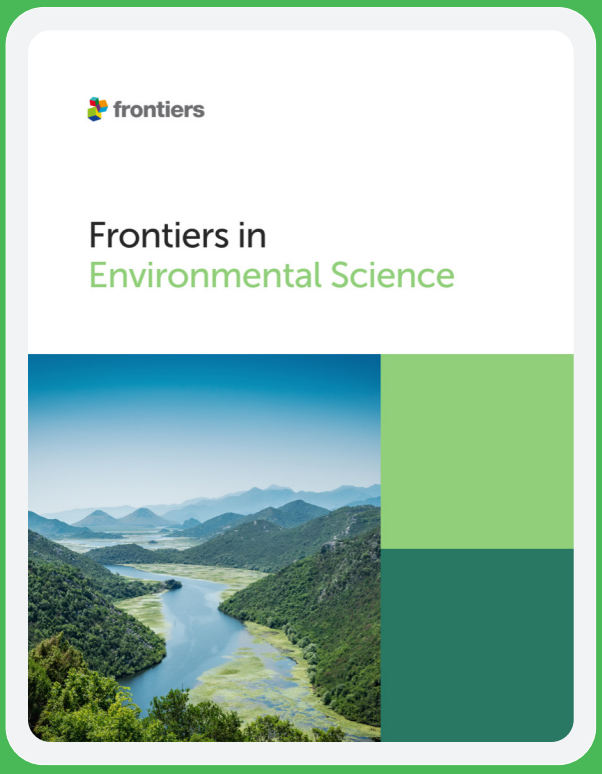
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