frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 24 November 2025
DOI 10.3389/fenvs.2025.1687405

OPEN ACCESS

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RECEIVED 17 August 2025
REVISED 26 October 2025
ACCEPTED 31 October 2025
PUBLISHED 24 November 2025

CITATION
Zhang Y, Bian R, Liu Y, Wang J and Zhao J (2025) Study of the impact of green finance reform and innovation pilot zones on total-factor carbon productivity in Chinese cities.
Front. Environ. Sci. 13:1687405.
doi: 10.3389/fenvs.2025.1687405

Study of the impact of green finance reform and innovation pilot zones on total-factor carbon productivity in Chinese cities

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With global climate change, environmental pollution, and other problems becoming increasingly prominent, realizing the green development of the economy has become an urgent issue for most countries. On the basis of the panel data of 282 cities in China from 2012 to 2022, an SBM-GML model is first applied to measure the total factor carbon productivity of cities; then, green financial reform and innovation pilot zones are established as a quasi-natural experiment, and a multi-period DID method is adopted to test the impact of green financial reform and innovation pilot zones on the total factor carbon productivity of cities in stages. The study reveals that (1) urban total factor carbon productivity can be significantly increased through the construction of green financial reform and innovation pilot zones, and this finding is robust; (2) the heterogeneity test reveals that the construction of green financial reform and innovation pilot zones can significantly increase total factor carbon productivity in the eastern, central and western regions, with the effect being more obvious in the western region; and (3) a mechanism test reveals that the construction of green financial reform and innovation pilot zones can enhance urban total factor carbon productivity by improving the level of green innovation and promoting the ecological industrial structure, whereas public environmental concern can effectively enhance the policy effect of green financial reform and innovation pilot zones on urban total factor carbon productivity. On the basis of the research findings, this paper provides a reliable reference for other countries hoping to implement green finance policies to realize low-carbon sustainable development and improve total factor carbon productivity.

KEYWORDS

green finance, pilot reform and innovation zones, urban total factor carbon productivity, difference-in-differences, quasi-natural experiment

1 Introduction

With the rapid development of the economy, ecological and environmental problems have become increasingly prominent globally, and the strengthening of ecological civilization has become a major national development strategy. British petroleum (BP) data show that total world carbon emission levels have continued to increase, but the growth rate of carbon emissions has slowed in the last decade. The total carbon emissions of the world's major developed countries peaked in the mid-19th century and have shown a slow decline[1]. Owing to their late entry into industrial civilization, developing countries are still in the emission-increasing stage at present, and the International Energy Agency has noted in its Global Carbon Emissions Report 2023 that China's carbon dioxide emissions account for approximately 34% of global carbon dioxide emissions, and it continues to rank first in the world in global carbon dioxide emissions. Since 2020, China's carbon emissions have exceeded the total emissions of developed economies, and by 2023, they were 15% higher[2]. To address this global challenge, China formally proposed a "dual-carbon" goal in 2020 to promote green and low-carbon development. With the continuous improvement in the green financial system and market construction, green finance is gradually becoming a powerful tool to help China realize this "dual-carbon" goal. With the resumption of the establishment of the G20 Sustainable Finance Research Group in 2021, more countries worldwide have begun to formulate green financial policies, and improvements in the green financial service system have become an important theme in the global financial market. In June 2017, at the executive meeting of the State Council of China, it was decided that pilot zones aimed at reforming and innovating green financial services would be built in five provinces, each with their own focus and characteristics, as a new attempt to promote green financial services. These pilot zones provide additional investment options for enterprises and are committed to creating various sustainable business models. By the end of the third quarter of 2023, China ranked first in the world for providing green loans, with a balance of RMB 28.58 trillion, a year-over-year increase of 36.8%,; during the same period, the balance of the domestic green bond market was RMB 1.98 trillion, ranking second in the world. Moreover, remarkable results have been achieved in the construction of green finance. As a new form of green finance, green financial reform and innovation pilot zones conform to the reform direction of the green transformation and upgrading of the national economy and effectively promote the coordinated development of China's economy and the environment. China, as an important participant in and promoter of green finance, has laid a solid foundation for the healthy development of the global green financial market. By exploring the carbon reduction effects and effective pathways of green finance, it is possible to promote the international alignment of green finance standards, contribute to the improvement of global climate finance cooperation mechanisms, and provide valuable reference experiences for other countries, which has important practical significance for the green development of urban economies worldwide.

2 Literature review

The policies of the Green Finance Reform and Innovation Pilot Zones were proposed and implemented by China, and many Chinese scholars have focused on studying the impact of the pilot zone policy on the green transformation and upgrading of enterprises and the reduction in urban pollution and carbon emissions (Zhang Z. et al., 2023). Compared to other enterprises, the green financial reform and innovation pilot zone policy has a stronger role in promoting the green transformation of private enterprises, large-scale enterprises, capital-intensive enterprises, and small-scale responsible enterprises than and is also able to impose stricter financing constraints on large-scale and less profitable heavy polluters (Zhao et al., 2023; Sun et al., 2023; Zhang, 2023; Liu and Wang, 2023). The pilot areas can influence firms' green total factor productivity through financing constraints and environmental protection investment, but the mediating effect of technological innovation is not significant (Zhang et al., 2023b). Such a pilot policy can also promote green technological innovation within enterprises through social financing, talent support, and government financial support and, at the same time, can significantly promote the green innovation of polluting enterprises, while the effect of green innovation on green enterprises is not significant (Ran and Zhang, 2023; Cheng and Zhu, 2024). Regarding the study of regional pollution reduction and carbon reduction, some scholars believe that, compared with other regions, green financial reform and innovation pilot zones play a more significant role in promoting the sustainable development of regions with a lower level of financial development and industrialization but a higher level of technological innovation (Lin et al., 2023) and that compared with other types of cities, the pilot zone policy is better able to increase the green total factor productivity of megacities and resource cities (Zhang et al., 2022). In contrast, some scholars believe that the pilot policy has a significant effect on small and medium–sized cities, western regions, and regions with weaker innovation capacity and has more significant promotion effects on green total factor productivity (Liu Y. et al., 2024). Moreover, the pilot policy promotes mainly urban pollution reduction and carbon reduction by promoting urban green innovation, upgrading the industrial structure and reducing urban energy intensity (Zhang Z. et al., 2023; Huang and Zhang, 2021; Tong et al., 2024; Wang et al., 2021). Although the green financial reform pilot zone policy was proposed and implemented in China (Ozili, 2022), some countries worldwide have also implemented policies similar to those of the green financial reform and innovation pilot zones in China, and some scholars have conducted studies on countries that have implemented similar green financial policies. Most of the studies that have been conducted focus on the contribution of green finance policies to carbon emission reduction and confirm that green finance is the best financial strategy for reducing carbon dioxide emissions (Ozili, 2022; Meo and Abd Karim, 2022; Liu A. et al., 2024; Jia, 2023; Fang et al., 2022). A few scholars have studied the impact of green finance on

1 BP China (2024), BP World Energy Outlook, BP, https://www.bp.com.cn/zh_cn/china/home/news/reports.html.

2 IEA (2024), CO2 Emissions in 2023, IEA, Paris https://www.iea.org/reports/co2-emissions-in-2023, Licence: CC BY 4.0.

sustainable development from a global perspective and confirmed that green finance can greatly contribute to the development of renewable energy sources and that green finance is an important financing tool for the sustainable development agenda (Alharbi et al., 2023; Wang K. H. et al., 2022).

Currently, parametric and non-parametric methods are the main types used for the measurement of total factor carbon productivity in academia, with the former being represented mainly by the stochastic frontier. Currently, more studies use non-parametric methods than parametric methods to measure total factor carbon productivity(Cui et al., 2023; Amri et al., 2019; Chen and Yao, 2024; Yuan et al., 2023), and most scholars use the slack-based measure–Malmquist–Luenberger index (SBM–ML index) to measure total factor carbon productivity (Han et al., 2022; Wang Q. et al., 2022; Zhou et al., 2010). With respect to the factors influencing total factor carbon productivity, related studies have shown that green technology innovation can have an impact on high-income economies, whereas the impact on total factor carbon productivity is not significant in less developed economies (Du and Li, 2019). Moreover, some scholars have found that renewable energy consumption contributes to the increase in total factor carbon productivity by measuring total factor carbon productivity in selected countries worldwide, whereas the mediating effects of income inequality and urbanization weaken this effect. Furthermore, nonrenewable energy consumption inhibits the increase in total factor carbon productivity, and the mediating effects of income inequality and urbanization increase this inhibiting effect (Li and Liu, 2022). A few scholars have also studied total factor carbon productivity trends and reported that total factor carbon productivity generally tends to increase, which is driven mainly by technological advances, and that developing countries have performed slightly better than developed countries in terms of carbon emission efficiency improvements (Cui et al., 2023; Bai et al., 2019).

Overall, the literature on green financial reform and innovation pilot zones has focused mainly on the carbon emission reduction effect on cities and enterprises. Countries that have implemented similar green finance policies worldwide have also focused on the carbon emission reduction and sustainable development effects of these policies. Countries that have implemented similar green finance policies worldwide have also focused on the carbon emission reduction and sustainable development effects of these policies. Research on total factor carbon productivity has focused mainly on the measurement method and influence mechanism. Few studies have investigated the impact of the pilot policy on total factor carbon productivity and the impact of a pilot policy on the environmental governance efficiency within cities (Lin and Zhong, 2024; Yu et al., 2023; Cheng et al., 2023). On the basis of the analysis of the literature, the marginal contribution of this paper is reflected in the following three main aspects. First, the literature studies only the pollution reduction and carbon reduction effects of green financial reform and innovation pilot zones but does not study their comprehensive effects on urban economic development and carbon emissions. This research enriches and supplements the literature on the policy effects of green financial reform and innovation pilot zones. Second, through mechanism analysis, this work explores the intermediary effects between green financial reform and innovation pilot zones and total factor carbon productivity from various angles and proposes policy suggestions accordingly. Third, this study considers the spatial effects of green financial reform and innovation pilot zones on urban total factor carbon productivity, and a spatial Durbin model is constructed to study the spillover effects of such policies. This study aims to provide a reliable reference for individual countries hoping to utilize green finance policies to cope with global climate change.

3 Policy context and theoretical mechanisms

3.1 Policy context

To cope with the increasing environmental problems caused by global climate change, many countries have introduced different green financial policies to mitigate climate change risks. Table 1 shows a comparison of the green financial policies implemented by China and those implemented by some developed countries, which are mainly divided into five parts, such as green financial classification standards and green information disclosure policies. All the countries are currently actively exploring green financial policies that are suitable for their own national conditions to cope with the environmental problems caused by global climate change; however, no country has standardized its understanding and definition of green finance, and there is a lack of coordination between green financial policies and incentives for relevant investors and financial institutions. In recent years, China's green bond market has risen rapidly to become one of the world's largest issuers of green bonds, and at the same time, the scale of green credit has gradually grown so that China has become the world's second-largest credit market. Although the scale of China's green finance is expanding, there is still a gap between China and some developed countries that had an early start in the green finance market. In terms of the participation of financial institutions, Chinese financial institutions, under the guidance of policies, actively participate in green financial practices and increase the participation of small and medium-sized banks while encouraging large banks to play a leading role. Financial institutions in developed countries such as Europe and the United States developed green financing earlier and have actively innovated in the fields of green insurance and green funds while exploring the traditional green credit and green bond fields in depth. In terms of international influence, some developed countries, such as the European Union, have a pioneering advantage in the formulation of international standards for green finance and rule leadership, and their green finance standards and concepts have been widely recognized internationally, whereas some internationally renowned financial institutions, such as Citibank, have already achieved a high level of influence in the global green finance market. China is now enhancing its international influence in the field of green finance by strengthening its docking with international standards and actively participating in international cooperation to become an important force in promoting the development of global green finance.

3.2 Theoretical mechanisms

In recent years, China's green financial market has greatly expanded, and green financial reform and innovation pilot zones,

TABLE 1 Countries.

Dimension	China	EU	UK	USA	Singaporean
Green finance classification standard	Green industry guidance catalogue (2019 edition) green bond support project catalogue (2021 edition) green financing statistical system	EU classification scheme for sustainable finance, EU green bond standard, etc.	The UK green finance strategy and related regulations of financial regulators	No nationally harmonized standards	Singapore-asia taxonomy of sustainable finance
Green disclosure policy	Finding a balance between coercion and encouragement	Preference for mandatory disclosure	Combination of mandatory and voluntary disclosure requirements for large corporations and financial institutions	Gradual strengthening but with limitations	Preference for mandatory disclosure
Green central bank policies	Incorporating climate change risk into existing policy frameworks without adding new central bank functions	Integrating climate change into the monetary policy framework	Clarification of sustainable development goals in central bank functions	No concerted and definitive action has been taken at this time, and the impact has been felt through indirect means	Guided by monetary and regulatory policies
Industry self-regulation	"Top-down" engagement of financial institutions	The regulatory authority actively promotes the strategic system on the ground	Banks and other financial institutions are actively launching services	Partial agency participation but volatility exists	Active business under government guidance and regulation

as green credit outside the green financial exploration policy, serve to transform and upgrade the real economy by acting as a guide, innovate green financial products and services, and promote the development of green finance. Green financial reform and innovation pilot zones were established via a comprehensive green financial system to create a sustainable business model and promote green transformation and upgrading of the economy. Green financial reform and innovation pilot zones require the establishment of green industries. Projects prioritize the government service channel, and the preferential treatment of the governmental policy allows the development of local enterprises to reduce green industry costs (Huang and Zhang, 2021; Zhang H. et al., 2023). Enterprises tend to develop green production to increase their profitability, thus reducing carbon emissions and increasing total factor productivity. Second, the pilot zone encourages the development of green credit, enterprises obtain more adequate sources of capital, and under the supervision of the government, media, and other parties, more financial resources flow to energy savings and environmental protection and green emission reduction projects, which increases the supply of capital for green industries and low-carbon technologies, thus increasing total factor carbon productivity. Green financial reform and innovation pilot zones enhance market transparency through the establishment of perfect environmental rights and interest trading markets and a green financial risk prevention mechanism so that investors can accurately assess the degree of environmental risk and green value of enterprises, guide the effective flow of funds to environmentally friendly enterprises, improve the efficiency of capital utilization, and thus promote total factor carbon productivity enhancement within cities (Hu et al., 2021). On the basis of the above discussion, this paper proposes Hypothesis 1 as follows:

Hypothesis 1: Pilot zones for green financial reform and innovation can promote urban total factor carbon productivity.

The ecologicalization of the industrial structure is an advanced form of industrial development guided by the theory of industrial ecology, which is a synthesis of advanced, rationalized, and sustainable industrial structures. The green financial reform and innovation pilot zone policy encourages the development of green and low-carbon industries through policy guidance and capital allocation while restricting high-polluting and high-energy-consuming industries and increasing the financing constraints of polluting industries to increase the degree of resource flow to environmentally friendly and highly efficient industries. High-energy-consuming industries that cannot obtain financial support gradually reduce the scale of their production, whereas low-energy-consuming and low-polluting industries, after obtaining financial support, gradually reduce the scale of their production through the development of high-value-added and high-technology green products and promote the sustainability, advancement, and rationalization of the industry to promote the ecologicalization of the industrial structure (Tao and Yue, 2023). Second, through the construction of eco-industry clusters, the green finance reform and innovation pilot zone policy attracts more green enterprises to cluster in the pilot zone, and green enterprises are able to share resources and recycling efforts with regional enterprises through the establishment of green supply chain partnerships, producing scale effects and collaborative innovation effects among enterprises, thus effectively enhancing the ecological level of the industrial structure in the pilot zone. The ecologicalization of the industrial structure promotes the flow of production factors to more efficient sectors by constructing an efficient and coordinated industrial structure, thus effectively improving the resource utilization efficiency. In the process of industrial structure ecologicalization, polluting industries need to introduce environmentally friendly technologies and engage in the ecological transformation of the entire production and manufacturing process to form new economic growth points and increase high-quality development within the urban economy. At the same time, increasing the level of ecologization of the industrial structure in the pilot area can help promote the extension of the industrial chain in the green, low-carbon direction and can aid in the formation of green industry clusters in the pilot area; the emission and operating costs of individual enterprises can by reduced through the advantages

obtained by clustering, thus increasing the total factor carbon productivity of cities (Yang and Ma, 2022).

The green financial reform and innovation pilot zone policy promotes research and development (R&D) and the application of green technologies through policy incentives and market mechanisms, and enterprises and R&D organizations in pilot zones need to continuously improve their green innovation capabilities to obtain financial support. Pilot zones encourage the development of green credit, which provides a credit base for enterprises, effectively reduces the cost of green innovation for enterprises, and provides enterprises with the ability to engage in R&D to foster innovation. An improvement in the level of green innovation results in greater production efficiency and more advantageous products for enterprises, and the cost advantage enterprises experience increases as the competitive advantage of their products improves (Liu and Wang, 2023). Moreover, the pilot zone policy can provide financial support and risk sharing for the transformation of green innovation achievements in a region. The pilot zone promotes the deep integration of green technology and financial capital through the establishment of a green financial service platform, the integration of innovation resources in the region, and other measures to enhance the actual transformation capacity of enterprises toward green technology and the city's green innovation capacity. An improvement in the level of green innovation in cities leads to more green technology. These green technologies can reduce carbon emissions at the source of production, and increases in the level of green technology directly reduce carbon emissions, increase production efficiency, and provide other advantages, which greatly improve energy use efficiency, thus effectively reducing carbon emissions. This results in more economic output for the same energy input and increases the city's total factor carbon productivity (Irfan et al., 2022). Moreover, improvements in the level of green innovation can drive the technological progress and industrial upgrading of related upstream and downstream enterprises in the industrial chain; additionally, it can lead to a high green innovation level of enterprises through the development of unique green products and services, the formation of differentiated competitive advantages in the market, and increased production profits to further incentivise enterprises to engage in green technological innovation, forming a virtuous circle, jointly promoting the green development of the urban economy, and thus enhancing the total factor carbon productivity of cities.

Hypothesis 2: Pilot zones for green financial reform and innovation can increase the total factor carbon productivity of cities by improving the ecological level of the industrial structure and the level of green innovation.

The degree of public concern for the environment reflects the degree of importance that the public attaches to environmental protection and sustainable development. The public can play a supervisory role in efforts to overcome environmental issues, and the increase in the level of public environmental concern means that more members of the community have begun to pay attention to and participate in environmental protection; this is coupled with the media's coverage of environmental issues, which can encourage enterprises and the government to pay more attention to their own environmental behaviors and environmental performance. This social form of supervision helps in the effective implementation of the pilot zone policy, prompting enterprises and the government to take measures to develop a green economy. Moreover, an increase in the level of public environmental concern can strengthen the market-oriented role played by enterprises and the government. When low-carbon practices are adopted, the public preference for green products and services increases, and the market is more inclined to develop green industries and low-carbon technology, which further promotes urban total factor carbon productivity (Pope et al., 2024).

Hypothesis 3: Public environmental concern plays a moderating role in the impact of the relationship between green financial reform and innovation pilot zones on urban total factor carbon productivity.

The theoretical mechanism analysis framework of this paper is shown in Figure 1.

4 Research design

4.1 Model setting

Multiperiod difference-in-differences (DID) analysis is suitable for addressing situations where individuals in a group are subject to policy shocks at inconsistent points in time. Owing to the differences in the times that the pilot zones for green financial reform and innovation were implemented in various regions, to explore in depth the impact of the pilot zones for green financial reform and innovation on total factor carbon productivity, this study utilizes a multiperiod DID model and fixes the individual and point-in-time effects to explore the impact of the pilot zones for green financial reform and innovation on total factor carbon productivity. The benchmark regression model setting is as in Equation 1:

$$TFCP_{it} = \alpha_0 + \alpha_1 Gfripz_{it} + \alpha_2 X_{it}^{'} + u_i + v_t + \varepsilon_{it} \quad (1)$$

where $TFCP_{it}$ is total factor carbon productivity; α_0 is a constant term; $Gfripz_{it}$ is a policy variable, which consists of the cross-multiplier of $Treat_{it} \times Period_{it}$, of which $Treat_{it}$ is a dummy variable for the pilot area and takes a value of 1 if it is a pilot city in the pilot of green financial reform and innovation area and 0 otherwise; $Period_{it}$ is a dummy variable for the pilot period and takes a value of 1 after the pilot city implements the policy and 0 otherwise, with the cross-multiplication of the two items constituting the core explanatory variables; α_1 is the regression coefficient, which is the key concern of this paper; $X_{it}^{'}$ is a series of control variables; u_i denotes individual fixed effects; v_t denotes time fixed effects; and ε_{it} is a random error term.

According to the previous analysis, the pilot zones for green financial reform and innovation can affect total factor carbon productivity in the following two ways: via the level of green innovation and via the ecologicalization of the industrial structure. To further explore the mechanism of the effects of green financial reform and innovation pilot zones on total factor carbon productivity, referring to Jiang Boat's mechanism test method, a two-step method is used to construct a mediation effect test model (Ting, 2022), and the impact of the core explanatory variables on the mediating variables is modelled as in Equation 2:

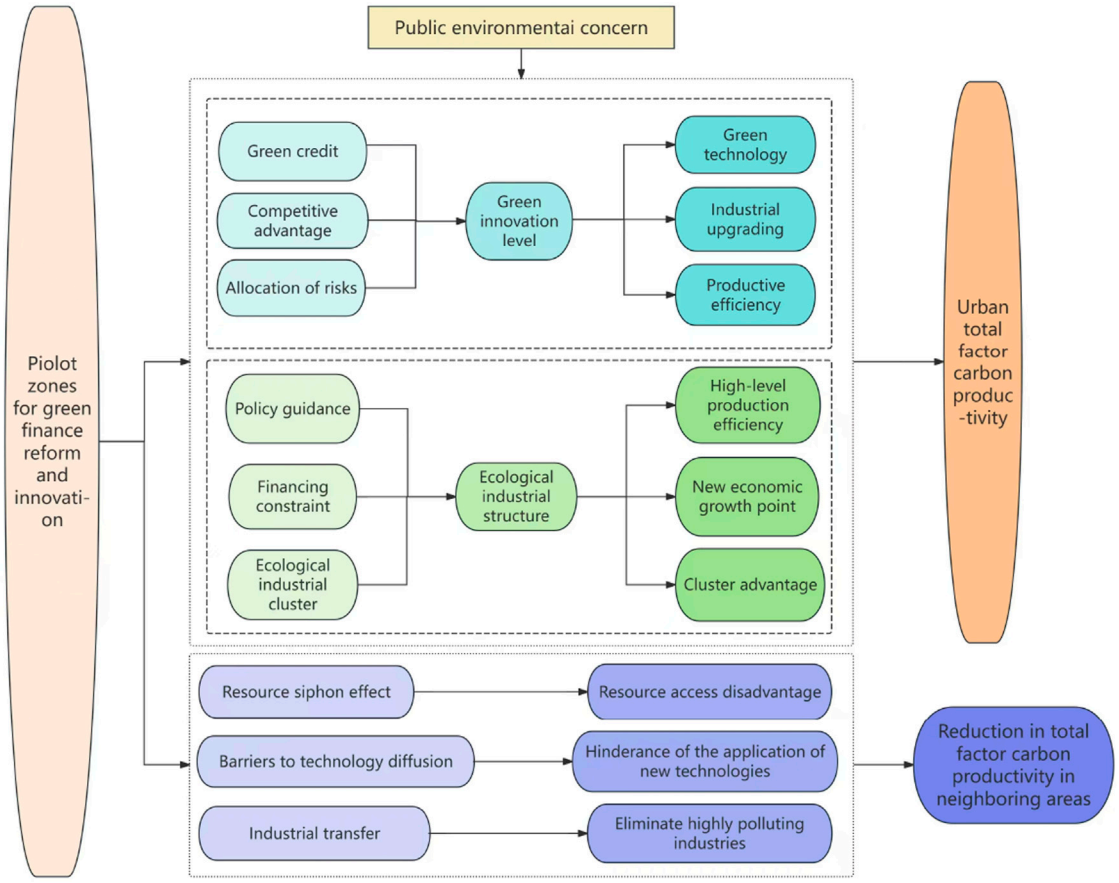

FIGURE 1
Analysis of theoretical mechanisms.

$$M = \alpha_0 + \alpha_3 Gfripz_{it} + \alpha_2 X_{it}^{'} + u_i + v_t + \varepsilon_{it} \quad (2)$$

where M is the mediating variable in this paper, which is the level of green innovation and the level of ecologicalization of the industrial structure, and the remaining variables are the same as above.

This work further constructs a moderating effect model to explore the effect of the green financial reform and innovation pilot zone mechanism on the impact of total factor carbon productivity; the specific model is as in Equation 3.

$$TFCP_{it} = \alpha_0 + \alpha_1 Gfripz_{it} + \gamma PEA_{it} + \delta Gfripz_{it} \times PEA_{it} + \alpha_2 X_{it}^{'} + u_i + v_t + \varepsilon_{it} \quad (3)$$

where PEA_{it} is the moderating variable, i.e., the degree of public environmental concern, and where δ is the coefficient of focus of the moderating effect.

4.2 Variable selection

4.2.1 Explained variables

The SBM-global Malmquist–Luenberger (GML) model is a more ideal method than the DID method for measuring production efficiency; the former accounts for the relaxation problem ignored by traditional data envelopment analysis (DEA) and can effectively mitigate the unsolvability problem of exponential linear programming. Therefore, the SBM-GML model is adopted to measure total factor carbon productivity, and the GML index calculation process is as in Equation 4:

TABLE 2 Green total factor carbon productivity indicators.

Level 1 indicators	Level 2 indicators	Interpretations
Inputs	Inputs	Fixed capital stock
		Total energy consumption
		Number of employees
Outputs	Expected outputs	Real GDP
	Non expected outputs	CO2 emissions

$$GML_{t-1}^{t} = \frac{1 + \overrightarrow{D_0^G}\left(x^{t-1}, y^{t-1}, b^{t-1}, y^{t-1}, -b^{t-1}\right)}{1 + \overrightarrow{D_0^G}\left(x^{t}, y^{t}, b^{t}, y^{t}, -b^{t}\right)} \quad (4)$$

A GML index greater than 1 or less than 1 indicates that the total factor carbon productivity is increasing or decreasing, respectively.

TABLE 3 Ecologicalization of the industrial structure.

Level 1 indicators	Level 2 indicators	Level 3 indicators	Direction of indicators
Ecologicalization of the industrial structure	Advanced industrial structure	Tertiary sector output/secondary sector output	+
	Rationalization of the industrial structure	Tyrell's index	-
	Sustainable industrial structure	Nonhazardous treatment rate of domestic waste	+
		Comprehensive utilization rate of general industrial solid waste	+
		Number of cell phones *per capita*	+
		Sum of the value added of secondary and tertiary industries	+
		Energy consumption per unit of GDP	-
		Emissions per unit of GDP	-
		Wastewater discharge per unit of GDP	-
		Smoke and dust emissions per unit of GDP	-

With reference to related studies, this study also takes 2011 as the base period to measure the total factor carbon productivity data of 282 prefecture-level cities from 2012 to 2022, and the specific indicators selected are shown in Table 2.

4.2.2 Core explanatory variables

In June 2017, with the consent of the State Council, the decision was made to implement a 5-year green financial reform and innovation trial in eight cities (new areas) in the five provinces (regions) of Zhejiang, Jiangxi, Guangdong, Guizhou, and Xinjiang. Then, in November 2019, Lanzhou city was approved to become a green financial reform trial area. On the basis of the panel data of 282 prefecture-level cities from 2012 to 2022, this paper adopts multitemporal DID empirical tests to examine the effects of green financial reform and innovation pilot zones on total factor carbon productivity. The core explanatory variables in this paper are green financial reform and innovation pilot zones, which are as dummy variables that take a value of "1" if the city is a pilot city and "0" otherwise. After the implementation of the policy, a value of "1" is assigned, and "0" is assigned otherwise. To exclude the influence of the policy effect lag, this work takes the following year after July 1 of the policy implementation year as the time of the policy shock; otherwise, the policy implementation year is regarded as the time of the policy shock.

4.2.3 Mediating variables

In this paper, the level of green innovation and the level of industrial structure ecologicalization are selected as mediating variables for analysis. The level of green innovation is measured by the logarithm of green invention patents plus one, and the ecological level of the industrial structure is measured following the methods of Gao Jinjie et al. (Jinjie and Weiwei, 2021; Wu et al., 2024). Three secondary indicators, i.e., advanced industrial structure, rationalization of the industrial structure and sustainable industrial structure, are selected, and the entropy method is used to measure the ecological level of the industrial structure. The specific indicators selected are shown in Table 3.

4.2.4 Moderating variables

This paper refers to related articles to select public environmental concern as a moderating variable for analysis and measures the degree of public environmental concern by compiling the annual average Baidu index, information index, and media index values for the residents in each city while searching for the keywords "haze" and "environmental pollution."

4.2.5 Control variables

With reference to existing studies, the control variables are as follows: (1) the level of economic development (ln*led*), measured by the logarithm of GDP; (2) the level of financial development (ln*fdl*), measured by the logarithm of the end-of-year balance of deposits in financial institutions; (3) the level of air pollution (ln*apl*), measured by the logarithm of the emissions of industrial sulphur dioxide; (4) the level of development of digital technology (ln*dtd*), measured by the logarithm of the number of internet broadband access subscribers; and (5) the level of the industrial structure (*isl*), measured by the share of employees in the secondary industry.

4.3 Data sources and explanations

The data used in this paper are drawn mainly from provincial statistical yearbooks, national statistical yearbooks, the national intellectual property patent database, the website of BeiDaFaBao, and an economic statistics database. To demonstrate the characteristics of the research data, this paper uses Stata 15 software to conduct descriptive analysis on the research data, resulting in Table 4. Numerically, The mean of total-factor carbon productivity is 0.9514, and the standard deviation is only 0.0967, much smaller than the mean, indicating that the sample has a low

TABLE 4 Descriptive statistics.

Variable symbol	Variable name	Observed value	Average value	Standard deviation	Minimum value	Maximum values
TFCP	Total factor carbon productivity	3,102	0.9514	0.0967	0.5101	1.4255
Gfripz	Pilot policy	3,102	0.0200	0.1270	0.0000	1.0000
ln*led*	Level of economic development	3,102	7.4594	0.9475	5.0331	10.7102
ln*fdl*	Level of financial development	3,102	17.0508	1.0626	14.5822	21.4766
ln*apl*	Air pollution levels	3,102	9.5037	1.3391	0.6931	13.1418
ln*dtd*	Level of development of digital technology	3,102	9.1730	1.5767	1.7918	17.1895
isl	Level of the industrial structure	3,102	3.6517	0.4323	0.9992	4.5706
eis	Ecologicalization of the industrial structure	3,102	0.0367	0.0258	0.0096	0.7944
gil	Level of green innovation	3,102	4.2598	1.7123	0.0000	10.0835
pec	Public environmental concerns	3,102	23.3769	27.2014	0.0000	164.5068

TABLE 5 Expansion variance factor test.

Variables	VIF	1/VIF
Gfripz	1.01	0.992373
ln*led*	1.01	0.991533
ln*fdl*	1.67	0.599931
ln*apl*	1.24	0.806607
Ln*dtd*	1.70	0.588521
isl	1.22	0.817063
VIF average	1.31	

degree of dispersion and overall strong stability. The standard deviation can reflect the degree of dispersion in a set of data. A large standard deviation in public environmental concern indicates significant differences in characteristics among individuals, which may be related to factors such as the public's level of environmental awareness and socio-economic conditions. The descriptive statistics of each variable are shown in Table 4.

5 Empirical analysis

5.1 Benchmark regression analysis

To avoid the effect of multicollinearity, this study uses the variance inflation factor (VIF) to further test whether there is the problem of multicollinearity among variables. The test results (Table 5) show that the variance inflation factor (VIF) values of the variables range from 1.01 to 1.70, which are much lower than the critical value of 10 recommended by scholars, and the tolerance (1/VIF) values range from 0.5999 to 0.9924, which are higher than the critical value of 0.1 recommended by scholars; thus, there is no multicollinearity among the variables in the regression model constructed in this study.

The effects of green financial reform and innovation pilot zones on total factor carbon productivity are shown in Table 6. Column (1) shows the results without adding control variables. Columns (2)-(6) present the results obtained by adding control variables sequentially on the basis of the baseline regression model; the coefficients of the core explanatory variables are all significantly positive after adding control variables and gradually increase, which means that after controlling for the influence of a series of factors, the establishment of green financial reform and innovation pilot zones can significantly improve total factor carbon productivity. Thus, Hypothesis 1 of this paper is supported.

The coefficients of the economic development level in columns (2)-(6) are significantly negative, indicating that, along with economic development, pollutant emissions have not been effectively curbed, which may be because long-standing environmental pollution problems are difficult to solve fundamentally in a short period. Moreover, with the rapid development of the economy, new environmental problems are constantly arising, which makes governance difficult, thus leading to an inversely related relationship between the level of economic development and total factor carbon productivity. The level of digital technology development is negatively correlated with total factor carbon productivity, which may be attributed to the fact that enterprises or cities fail to effectively manage and optimize resource allocation in the digital transformation process and over-invest in certain non-core digital technologies, leading to resource mismatches and efficiency losses, thus reducing total factor carbon productivity.

5.2 Robustness tests

5.2.1 Parallel trend test

The parallel trend test ensures that there is no obvious time trend difference in total factor carbon productivity between the experimental group and the control group before the policy

10.3389/fenvs.2025.1687405

TABLE 6 Benchmark regression.

Variables	Explained variable: Total factor carbon productivity					
	(1)	(2)	(3)	(4)	(5)	(6)
Gfripz	0.0338*** (0.0065)	0.0357*** (0.0066)	0.0358*** (0.0066)	0.0358*** (0.0066)	0.0361*** (0.0065)	0.0368*** (0.0065)
ln*led*		−0.0208** (0.0093)	−0.0207** (0.0093)	−0.0207** (0.0093)	−0.0206** (0.0093)	−0.0210** (0.0093)
Ln*fdl*			0.0003 (0.0010)	0.0003 (0.0010)	0.0017 (0.0013)	0.0014 (0.0013)
ln*apl*				0.0001 (0.0008)	−0.0003 (0.0009)	−0.0008 (0.0009)
Ln*dtd*					−0.0015* (0.0008)	−0.0014* (0.0008)
isl						0.0040 (0.0027)
Constant	0.9508*** (0.0010)	1.1058*** (0.0693)	1.0999*** (0.0737)	1.0989*** (0.0743)	1.0920*** (0.0741)	1.0890*** (0.0741)
Year FE	Y	Y	Y	Y	Y	Y
City FE	Y	Y	Y	Y	Y	Y
R-squared	0.6452	0.6458	0.6457	0.6456	0.6458	0.6460
N	3,102	3,102	3,102	3,102	3,102	3,102

Robust standard errors in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.

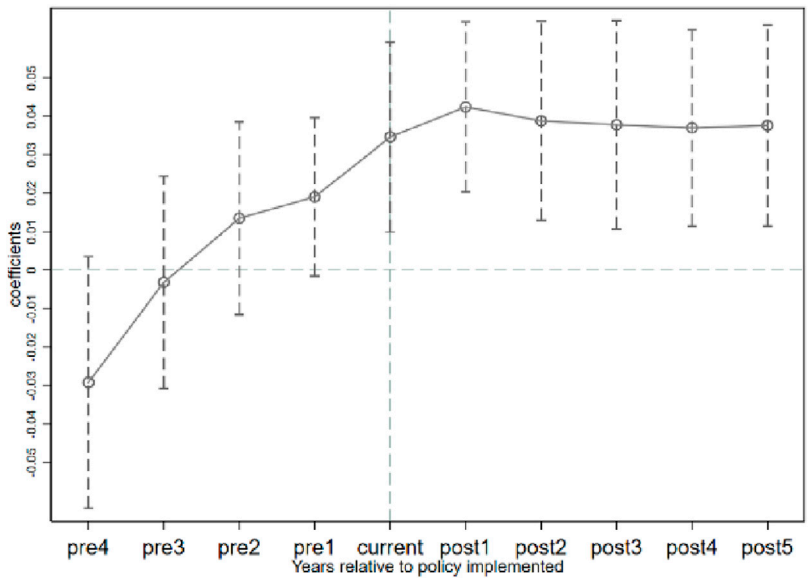

FIGURE 2
Parallel trend test.

implementation; i.e., this test ensures that the policy implementation is the main factor that is causing the difference rather than other potential time trend differences. The mean values of the coefficients before the implementation of the policy are removed. The results are shown in Figure 2. In the horizontal coordinate, "current" is the time of policy implementation, and on the left side of the value of "current" is the time before the policy shock occurs. The total factor carbon productivity shows an upwards trend, but the estimated coefficients are all over the 0-axis, i.e., no significant difference between the development of the experimental group and the control group is observed, nor is there a significant trend difference in the development of total factor carbon productivity. The productivity development of the experimental group and the control group did not show obvious differences or significant differences in development trends. After the implementation of the policy, the estimated coefficients are significantly greater than 0. The experimental group and the control group show obvious differences in their total factor carbon productivity development trends, indicating that the total factor carbon productivity of the experimental group improved significantly after the implementation of the policy and over the long term.

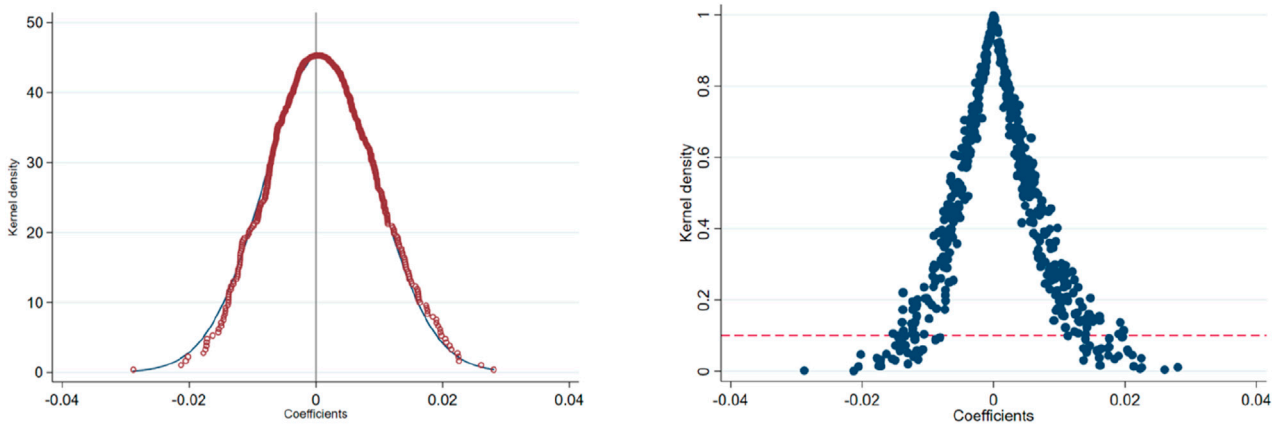

FIGURE 3
Placebo test.

5.2.2 Placebo test

The placebo test, as a counterfactual test, is able to exclude accidental results caused by other potential factors. In this work, we use the method of randomly setting a dummy experimental group to exclude the influence of chance factors. First, among the 282 sample cities, 9 cities are randomly selected as the pseudotreatment group, and the remaining cities constitute the control group. On the basis of this grouping, a policy dummy variable is generated, which is repeated 500 times. The results obtained are shown in Figure 3.

The left panel in Figure 3 shows the placebo test coefficient plot, in which the curve formed by the red circles is the coefficient distribution of the random sample, and in this plot, most of the random coefficients are concentrated around zero, indicating that the dummy policy time nodes have less influence on the economic target setting. The right panel in Figure 3 shows the p value distribution of random sampling, in which the horizontal line perpendicular to the vertical axis is P = 0.1. If most of the scatter points are located below this line, then the coefficients are significant at least at the 10% level, which means that the randomly selected pseudo-treatment group appears to be different before and after the policy shocks, and *vice versa*, indicating that there is no significant difference during these two periods for this group. It is clear from the p value distribution that most of the estimated coefficients are not significant, indicating that the randomly selected experimental group does not show significant differences before and after the policy implementation, which indicates that the green financial reform and innovation pilot areas are not affected by other potential factors and proves that the previous results are more reliable than these results are.

5.2.3 Bacon decomposition

Due to the differences in the establishment time of the Green Finance Reform and Innovation Pilot Zones, the multi-period DID model estimation may produce heterogeneous treatment effects that vary across groups and time dimensions, which could lead to biased estimation results. This paper follows the approach of Goodman-Bacon (2021) by grouping the panel data according to different treatment times (Goodman-Bacon, 2021).

TABLE 7 Bacon decomposition.

DD Comparison	Avg DD Est	Weight
Earlier T vs. Later C	−0.020	0.002
Later T vs. Earlier C	0.001	0.001
T vs. Never treated	0.034	0.997
Diff-in-diff estimate: 0.034		

Table 7 shows that after considering the pre-experiment and post-experiment groups at different time points, 99.7% of the net effect of green financial reform and innovation pilot zones on urban total-factor carbon productivity comes from the non-experiment and experiment groups. In other words, the vast majority of the policy effect is derived from counterfactual analysis using the non-experiment group as the control group, indicating that the empirical results of this study are not biased due to heterogeneous treatment effects and that the regression results are robust.

5.2.4 Endogeneity test

Given that the green financial reform and innovation pilot zones comprehensively consider the test area when choosing policy pilots, which makes the selection of policy samples appear nonrandom and affects the test effect of the green financial reform and innovation pilot zones on total factor carbon productivity, an endogeneity problem exists. On the basis of Wang Fengting et al.'s approach (Fengting et al., 2024), the policy dummy variable of green financial reform and innovation pilot zones lagged to the first order is analysed as an instrumental variable, and the regression estimation of the econometric model set in the previous section is performed via two-stage least squares (2SLS) regression; the results are shown in Table 8.

In Table 8, columns (1) and (2) show the regression results of the first and second stages, respectively. In the first stage, the instrumental variables are significantly and positively correlated with the core explanatory variables at the 1% level, and in the second stage, the core explanatory variables are significantly and

TABLE 8 Endogeneity test.

Variables	Instrumental variable approach	
	(1)	(2)
Gfripz		0.0309** (0.0151)
L.*Gfripz*	0.8035*** (0.0116)	
Control	Y	Y
Year FE	Y	Y
City FE	Y	Y
Underidentification test		1,663.380 [0.0000]
Weak identification test		4,798.3190 {16.38}
R-squared	0.6554	0.0233
N	2,820	2,820

The Kleibergen–Paap rk LM, statistic was used for the under-recognition test, and the numbers in [] are its p value; the Donald Wald-F, statistic was consulted for the weak recognition test, and the Stock–Yogo test 10% level critical value is in {}.
Robust standard errors in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.

TABLE 9 Other robustness tests.

Variables	Robustness check					
	(1) Shrinkage treatment	(2) Variable lag	(3) Municipalities	(4) Exclusion of other policies	(5) PSM-DID	(6) Heckman
Gfripz	0.0368*** (0.0065)	0.0348*** (0.0073)	0.0330*** (0.0055)	0.0391*** (0.0078)	0.0359*** (0.0063)	0.4521*** (0.1019)
Imr						−0.1752*** 0.0419
Constant	1.0890*** (0.0741)	1.0548*** (0.0787)	0.8775*** (0.0228)	1.0900*** (0.0742)	0.9950*** (0.0699)	1.0383*** 0.1273
Control	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y
City FE	Y	Y	Y	Y	Y	Y
R-squared	0.6460	0.6409	0.6642	0.6455	0.6539	0.7839
N	3,102	2,820	3,058	3,080	2,932	1974

Robust standard errors in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.

positively correlated with total factor carbon productivity at the 1% level. The instrumental variables are subjected to a test of underrecognition and a test of weak recognition. The Kleibergen–Paap rk LM statistic was used for the underidentification test, with a p value (p value = 0.0000) of less than 0.01 indicating significance at the 1% level, rejecting the original hypothesis of "underidentification of instrumental variables", i.e., the selection of instrumental variables in the article meets the assumption of relevance. The Donald Wald-F statistic is used for the weak identification test; a value greater than 10 indicates that there is no weak instrumental variable, and the results show that the selection of instrumental variables is reasonable, indicating that the choice of instrumental variables is reasonable and that after adding instrumental variables, the construction of green financial reform and innovation pilot zones can still significantly improve total factor carbon productivity.

5.2.5 Other robustness tests

The other robustness tests performed are presented in Table 9. Since the statistical accuracy of the data and other unobservable factors may lead to the presence of extreme sample values in the data, the effect of extreme values on estimation and inference can be significantly reduced by a shrinking-tail treatment. Therefore, the explanatory variables are subjected to 1% two-sided tailoring, and the results are shown in column (1) of Table 9. Owing to the possible serial correlation and autocorrelation of the explanatory variables, total factor carbon productivity with a one-period lag is included as

an explanatory variable in the model for regression, and the results are shown in column (2) of Table 9. The results are all significantly positive (p value = 0.000), indicating that the previous results are still robust. Municipalities directly under the central government have better economic conditions and resources than ordinary prefecture-level cities and, thus, are excluded from the test; the results are shown in column (3) of Table 9, and the regression results are significantly positive at the 1% level (p value = 0.000). During the sample selection period of this paper, the National Development and Reform Commission (NDRC) identified two batches of low-carbon pilot cities in 2012 and 2017. To exclude the impact of the implementation of this policy on the results of this paper, the regression is performed after the low-carbon pilot cities and the pilot cities of the pilot zones for green financial reform are excluded. The results are shown in column (4) of Table 9. The core explanatory variables are positive and significant at the 1% level (p value = 0.000), confirming the robustness of the results of the previous paper. Propensity score matching (PSM)-DID analysis can effectively solve the problem of selection bias in causal inference, which can ensure that the experimental group and the control group have similar characteristics and thus reduce the risk of selection bias. This study adopts radius matching to carry out exact matching between the control group and the experimental group and strictly screens and excludes the data with poor matching results. The results of the balance test are shown in column (5) of Table 9, and the coefficients of the core explanatory variables are all significantly positive after matching (p value = 0.000), which indicates that total factor carbon productivity can still be increased through the construction of green financial reform and innovation experimental zones increase, and the above regression results are still robust, even after accounting for selection bias in the samples. To further alleviate the possible sample selection bias problem, this paper adopts the Heckman two-stage model to test the samples and uses the logarithm of the number of municipal bank outlets as an instrumental variable. On the one hand, the number of urban bank outlets is an important consideration in the selection of green financial reform and innovation pilot zones and satisfies the principle of relevance of instrumental variables. On the other hand, the number of bank branches does not directly affect the total factor carbon productivity of cities, which satisfies the principle of exogeneity. The instrumental variable is introduced into the model to calculate the inverse mill's ratio (Imr) and is substituted into the second stage of the regression. The results are shown in Table 9 (6), in which the inverse mill's ratio is significant at the 1% level (p value = 0.000), indicating that there is a nonnegligible sample selection bias in the samples. After the addition of the inverse mill's ratio in the second stage, the core explanatory variables are still significantly positive, indicating that after the sample selection bias issue is considered, the construction of the pilot area can still enhance the total factor carbon productivity of the city.

5.3 Heterogeneity analysis

5.3.1 Regional heterogeneity

Different pilot regions have large differences in their economic environments, industrial structures, and other aspects due to differences in geographic location. To explore the regional differences in the impacts of green financial reform and innovation pilot zones on total factor carbon productivity, 282 prefecture-level cities are divided into three regions—the eastern, central, and western regions—according to the traditional geographic division to further explore the effects of the establishment of green financial reform and innovation pilot zones on cities' total factor carbon productivity. The results of the regional heterogeneity analysis are shown in Table 10. Columns (1), (2), and (3) of Table 10 show the estimation results of the effects of the construction of the green financial reform and innovation pilot zones on total factor carbon productivity in the eastern, central, and western regions, respectively; the regression coefficients of the core explanatory variables in these regions are all significantly positive, which indicates that the construction of the green financial reform and innovation pilot zones can effectively increase total factor carbon productivity at the nationwide scale, with the core explanatory variables in the western region having significant positive coefficients. Among these three regions, the coefficient of the core explanatory variables in the western region is larger, indicating that green financial reform and innovation pilot zones play a stronger role in promoting total factor carbon productivity in the western region. The probable reason is that the policy of the pilot zone provides more sources of funds for the west through the innovation of green financial products and services and improves the efficiency of resource utilization in the western region, thus overcoming the financial and technological disadvantages of the western region to a certain extent so that the original resource disadvantages of the western region have been significantly improved under the policy effect of the pilot zone (Huang and Zhang, 2021; Yingying et al., 2024). Moreover, the green financial reform and innovation pilot zone policy aims to support green economic development and improve the green economy through financing. Moreover, the green financial reform and innovation pilot zone policy aims to support the development of the green economy through financial means and improve the effectiveness of the green industry, which is more targeted to the relatively backwards western region and helps compensate for its shortcomings in finance, technology, etc. Thus, the effect of the innovation pilot zone policy on the promotion of total factor carbon productivity in the western region is stronger, whereas the central and eastern regions have higher levels of economic development and more

TABLE 10 Regional heterogeneity.

Variables	Regional heterogeneity		
	(1) Eastern	(2) Central	(3) Western
Gfripz	0.0182** (0.0091)	0.0258*** (0.0087)	0.0509** (0.0199)
Constant	0.9369*** (0.0890)	0.5672*** (0.1531)	0.9500** (0.3886)
Control	Y	Y	Y
Year FE	Y	Y	Y
City FE	Y	Y	Y
R-squared	0.6112	0.6903	0.7145
N	1,595	1,287	220

Robust standard errors in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.

TABLE 11 Factor heterogeneity.

Variables	Factor heterogeneity	
	(1) TC	(2) EC
Gfripz	0.0143* (0.0084)	0.0243*** (0.0073)
Constant	0.8349*** (0.0654)	1.3059*** (0.0747)
Control	Y	Y
Year FE	Y	Y
City FE	Y	Y
R-squared	0.6923	0.6335
N	3,102	3,102

Robust standard errors in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.

mature and stable financial systems than the western regions do; the eastern and central regions need more time to adapt to the new policy tools, leading to a weaker policy promotion effect (Muxi and Yubo, 2023).

5.3.2 Factor heterogeneity

The GML index can be further decomposed into technical progress (TC) and technical efficiency (EC), and total factor carbon productivity is tested after decomposing it into technical progress and technical efficiency (Abidin et al., 2023). The results are shown in columns (1) and (2) of Table 11 and are significantly positive, and the regression coefficients of the core explanatory variables on technical efficiency are larger, which suggests that green financial reform and innovation pilot zones enhance total factor carbon productivity mainly through influencing technical efficiency.

5.3.3 City size heterogeneity

In the process of enhancing total factor carbon productivity in green financial reform and innovation pilot zones, city size may have an impact on the policy effect. To further analyse the impact of city size on the carbon emission reduction effect in the context of green financial reform and innovation pilot zones, this work categorizes city size and constructs a difference-in-difference-in-differences (DDD) model, as in Equation 5:

$$TFCP_{it} = \alpha_0 + \beta_1 Gfripz_{it} \times CS_{it} + \alpha_1 Gfripz_{it} + \beta_2 Treat_{it} \times CS_{it} + \beta_3 Period_{it} \times CS_{it} + \alpha_2 X_{it} + u_i + v_t + \varepsilon_{it} \quad (5)$$

where CS_{it} is a dummy variable for city size, $Gfripz_{it} \times CS_{it}$ is a DDD term, and the remaining variables are the same as those in the previous section.

In Table 12, the DDD terms of provincial capital cities and subprovincial cities are all significantly positive, indicating that the policy effects of provincial capital cities and subprovincial cities are more obvious than those of other cities are, probably because these cities occupy an important position in China's administrative system and are the political, economic, and cultural centres of their respective provinces or regions; thus, the pilot policy can be implemented more smoothly in these cities. The DDD scores for general cities are significantly negative, probably because cities in general are weaker than provincial capitals and subprovincial cities in terms of their ability to acquire resources such as capital, technology, and talent, thus limiting the promotion of the green financial reform and innovation pilot zone policy. Moreover, the economic structures of cities in general are relatively homogeneous, with a relatively large proportion of traditional industries and high-pollution enterprises, which is not conducive to the implementation of the pilot zone policy, thus temporarily inhibiting the increase in total factor carbon productivity.

6 Further analysis

6.1 Mechanism test

6.1.1 Level of green innovation

According to previous research results, green financial reform and innovation pilot zones can significantly increase total factor carbon productivity. To further study the mechanism through which

TABLE 12 Urban scale heterogeneity.

Variables	Urban scale heterogeneity		
	(1) Provincial capital cities	(2) Subprovincial cities	(3) General urban cities
DDD	0.0379*** (0.0125)	0.0990*** (0.0291)	−0.0379*** (0.0125)
Gfripz	0.0204*** (0.0061)	0.0255*** (0.0049)	0.0583*** (0.0114)
Constant	1.0906*** (0.0741)	1.0866*** (0.0741)	1.0906*** (0.0741)
Control	Y	Y	Y
Year FE	Y	Y	Y
City FE	Y	Y	Y
R-squared	0.6462	0.6467	0.6462
N	3,102	3,102	3,102

Robust standard errors in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.

TABLE 13 Level of green innovation.

Variables	Number of green innovation patents filed in the year		
	(1) Nationwide	(2) Resource-based cities	(3) Non-resource-based cities
Gfripz	0.1448** (0.0658)	−0.2626* (0.1435)	0.1950*** (0.0688)
Constant	0.5945 (0.5492)	1.1686 (1.0542)	0.7322 (0.6666)
Control	Y	Y	Y
Year FE	Y	Y	Y
City FE	Y	Y	Y
R-squared	0.9384	0.8573	0.9413
N	3,102	396	2,706

Robust standard errors in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.

TABLE 14 Ecologicalization of the industrial structure.

Variables	Ecologicalization of the industrial structure		
	(1) Nationwide	(2) Resource-based cities	(3) Nonresource-based cities
Gfripz	0.0056** (0.0022)	0.0112 (0.0076)	0.0050** (0.0023)
Constant	0.0209 (0.0474)	−0.0022 (0.0326)	0.0457 (0.0642)
Control	Y	Y	Y
Year FE	Y	Y	Y
City FE	Y	Y	Y
R-squared	0.6462	0.2371	0.5154
N	3,102	396	2,706

Robust standard errors in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.

green financial reform and innovation pilot zones impact total factor carbon productivity, this study applies a two-step method to test the factors affecting total factor carbon productivity, and the results are shown in Tables 13, 14. Table 13 shows the regression results when the level of green innovation is taken as the mediating variable; column (1) presents the regression results of the whole sample, and the regression coefficient of the core explanatory variables is significantly positive (p value = 0.014), indicating that the construction of green financial reform and innovation pilot zones effectively promotes urban green innovation. To strengthen key tasks such as environmental governance and ecological protection and promote sustainable development, the State Council promulgated the National Sustainable Development Plan for Resource-based Cities (2013–2020), according to which this paper divides the sample cities into resource-based cities and nonresource-based cities. Columns (2) and (3) present the regression results when the sample is divided into resource-based cities and nonresource-based cities, and the regression coefficients of the former are significantly negative. The possible reason for this is that resource-based cities have long relied on traditional resource-based industries, resource-based industries are usually characterized by high energy consumption and high emissions, and resource-based industries face greater financing constraints owing to the implementation of the green financial reform pilot zone policy, which leads to difficulties in obtaining sufficient financial support for industrial upgrading and energy efficiency, whereas resource-based cities faces obstacles from traditional industries regarding their green innovation capacity, resulting in a negative impact of the green financial reform and innovation pilot zone policy on the level of green innovation in resource-based cities. This leads to the green financial reform and innovation pilot zone policy having a negative impact on the level of green innovation in resource-based cities (Xu et al., 2024).

6.1.2 Ecologicalization of the industrial structure

Table 14 shows the regression results when taking the ecologicalization of the industrial structure as a mediating variable, where column (1) presents the results of regressing the whole sample, and columns (2) and (3) present the regression results of resource-based cities and nonresource-based cities, respectively; the regression coefficient of the whole sample is significantly positive (p value = 0.011). This finding indicates that green financial reform and innovation pilot zones can effectively guide financial resources towards the green industry; reduce the degree of financial support for high-polluting, high energy-consuming industries; and promote the development of the industrial structure in the direction of ecologicalization. The regression coefficient of nonresource-based cities is significantly positive, indicating that the green financial reform and innovation pilot zone policy can significantly enhance the industrial structure ecological levels of these cities, which are

TABLE 15 Public environmental concern.

Variables	Public environmental concern		
	(1) Nationwide	(2) Resource-based cities	(3) Nonresource-based cities
Gfripz × *pec*	0.0005*** (0.0002)	0.0053 (0.0093)	0.0006*** (0.0002)
Gfripz	0.0141* (0.0080)	0.0137 (0.0427)	0.0080 (0.0073)
pec	0.0013*** (0.0002)	−0.0006 (0.0005)	0.0014*** (0.0002)
Constant	1.1330*** (0.0745)	0.9292*** (0.1651)	1.2176*** (0.0816)
Control	Y	Y	Y
Year FE	Y	Y	Y
City FE	Y	Y	Y
R-squared	0.6532	0.5048	0.6637
N	3,102	396	2,706

Robust standard errors in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.

relatively flexible in terms of their industrial structure, have multiple industrial sectors, and are prone to accepting emerging green industries and technologies. Moreover, nonresource-based cities pay more attention to ecological environmental protection and sustainable development than resource-based cities do, which provides a good social foundation for green financial reform and innovation and, thus, can promote the ecologicalization of the industrial structure more effectively. The regression coefficient of resource-based cities is not significant, probably because these cities are dominated mainly by a resource-based industrial economy in the early stage, which has a single industrial structure, insufficient economic backbone, strong dependence on resources, and faces more difficulties in transforming the industry; at the same time, the dominant industries in resource-based cities tend to be traditional industries with high levels of energy consumption and emissions, and the pushback mechanism of the pilot zone policy on traditional industries may be weakened by the protectionism of the local government, the path dependence of enterprises, etc. Thus, Hypothesis 2 is verified.

6.1.3 Public environmental concern

Table 15 shows the results of incorporating public environmental concern into the moderated effects model, where column (1) presents the results of the full-sample regression, and columns (2) and (3) present the results of the regressions of resource-based cities and nonresource-based cities, respectively; the interaction term of the full sample is significantly positive (p value = 0.001), indicating that public environmental concern positively contributes to the effects of the green financial reform and innovation pilot zone policy, which is in line with the previous hypotheses. The interaction term for nonresource-based cities is significantly positive, indicating that public environmental concern positively promotes the effect of the green financial reform and innovation pilot zone policy on nonresource-based cities, with the residents of these cities paying more attention to the protection of the ecological environment and sustainable development than to other factors, which strengthens the supervision of the implementation process of the policy. Moreover, nonresource-based cities have well-developed social service facilities, and residents have more ways to supervise policy implementation, which ensures that the policy is effectively implemented. The interaction term for resource-based cities is not significant, probably because the incomes of workers in these cities are lower than the national per capital income levels of urban residents, and social problems are prominent, which makes it difficult for residents of resource-based cities to actively participate in the green transition. Moreover, although the increase in public environmental concern can enhance the social consensus on green development, it makes changing the economic structure and industrial characteristics of resource-based cities difficult in the short term.

TABLE 16 Moran's global index.

Year	Total factor carbon productivity	Pilot policy
h2017	0.057***	0.042***
h2018	0.068***	0.042***
h2019	0.076***	0.042***
h2020	0.104***	0.033**
h2021	0.104***	0.033**
h2022	0.104***	0.033**

***p < 0.01, **p < 0.05, *p < 0.1.

6.2 Spatial measurement analysis

The inverse square matrix of spatial geographic distance is used to analyse the spatial effects of the pilot policy, and first, a spatial autocorrelation test between the pilot policy and total factor carbon productivity in 282 cities between 2017 and 2022 is conducted via Moran's global index. As shown in Table 16, the test results indicate that all Moran's index values greater than 0 pass the significance test, indicating that there is a significant positive spatial correlation between the pilot policy and total factor carbon productivity. Figure 4 shows Moran's scatterplot of total factor carbon

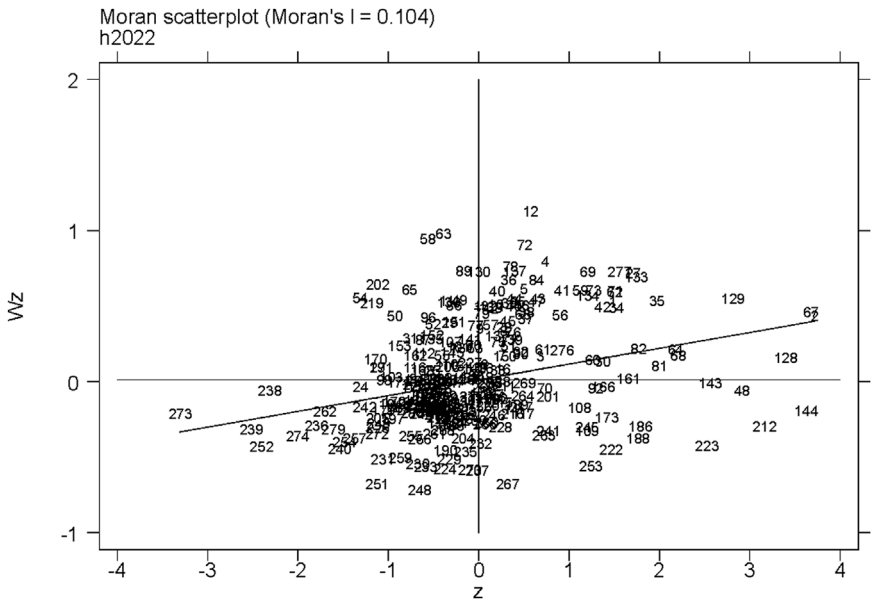

FIGURE 4
Localized Moran's index.

TABLE 17 LM test.

Test	Test Type	Statistic	df	p value
Spatial error	Moran's I	30.745	1	0.000
	LM	931.468	1	0.000
	Robust LM	622.774	1	0.000
Spatial lag	LM	515.284	1	0.000
	Robust LM	206.590	1	0.000

productivity, which presents a "high high–low low" aggregation pattern. In general, a spatial correlation exists between the pilot policy and total factor carbon productivity, which provides a basis for selecting the spatial econometric model for further analysis (Zhang et al., 2023d).

In the process of model selection, a Lagrange multiplier (LM) test is conducted. On the basis of the discriminant criteria proposed by previous scholars, when the statistic of the LM error test is significant, use of the spatial error model (SEM) is preferable; if this statistic is not significant, then use of the spatial lag model (SAR) is preferable. In contrast, if the statistic of the LM lag test is significant, then use of the SAR is preferable; if this statistic is not significant, then use of the SEM is preferable. According to the results of the LM test in Table 17, the statistics of both tests are significant, indicating that both spatial lag and spatial error effects need to be considered in the analysis. Therefore, the spatial Durbin model should be chosen to examine the spatial effects of green financial reform and innovation pilot zones on total factor carbon productivity.

The spatial Durbin model is further subjected to the LR test, Wald test, and Hausmann test, and the double fixed effects model of the spatial Durbin model is selected for further analysis on the basis of the test results; the results are shown in Table 18. In Table 18, column (1) presents the overall regression results, and columns (2), (3), and (4) present the results of partial differential decomposition, which indicate the direct effect, the spatial spillover effect, and the total effect, respectively. Among them, the direct effect is significantly positive, indicating that the implementation of the pilot zone policy in the region has a positive effect on total factor carbon productivity, and the indirect effect is significantly negative, indicating that the implementation of the pilot zone policy has a negative effect on total factor carbon productivity in neighbouring regions. This finding may be because the local implementation of the green financial reform and innovation pilot zones attracted green financial resources and investments that would otherwise flow to neighbouring regions, resulting in a relative lack of key production factors such as capital, technology, and talent in neighbouring regions, which in turn limited improvements in their total factor carbon productivity.

7 Conclusions and recommendations

7.1 Conclusions

On the basis of the panel data of 282 cities in China from 2012 to 2022, this study evaluates the mechanism and effect of the pilot zone policy in driving the green development of cities, using the total factor carbon productivity of each city as the explanatory variable and the implementation of the green financial reform and innovation pilot zone policy as the core explanatory variable. The results are as follows. (1) Green financial reform and innovation pilot zones can significantly increase the total factor carbon productivity of cities, but the implementation of such policies has a negative spatial spillover effect on the total factor carbon productivity of neighbouring cities. (2) The construction of a

TABLE 18 Decomposition of spatial effects.

Variables	Spatial effects			
	(1) Main	(2) Direct effect	(3) Indirect effect	(4) Aggregate effect
Gfripz	0.0505*** (0.0108)	0.0468*** (0.0112)	−0.2431** (0.1135)	−0.1962* (0.1158)
rho	0.4828*** (0.0407)			
Sigma2_e	0.0026*** (0.0000)			
Control	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
City FE	Y	Y	Y	Y
R-squared	0.1783	0.1783	0.1783	0.1783
N	3,102	3,102	3,102	3,102

Robust standard errors in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.

pilot zone can significantly increase total factor carbon productivity in the eastern, central, and western regions, with the enhancement effect being more obvious in the western region. (3) The construction of green financial reform and innovation pilot zones can increase the total factor carbon productivity of cities by increasing the level of green innovation and promoting the ecological industrial structure.

7.2 Policy recommendations

China's policy of implementing pilot zones for green financial reform and innovation has made a positive contribution to addressing the environmental problems caused by climate change, and countries can draw on China's policy experience to realize the green development of their own economies. Specifically, countries can strengthen the leading role of the government in the development of green finance. China's pilot zone policy involves planning and guiding from a macro perspective while focusing on the coordination between various sectors, and other countries can formulate a systematic green finance policy framework that clarifies the responsibilities of various sectors while strengthening intersectoral synergies and cooperation to form policy synergies. Second, China's pilot zones implement differentiated green financial policies according to the geographic advantages and resource endowments of different regions, etc. Other countries need to formulate green financial policies according to local conditions to improve the pertinence and effectiveness of policies. Finally, financial institutions in China's pilot areas have actively innovated and launched a variety of financial products, such as green credit and green funds, to meet the needs of different green projects and investors. At present, countries with earlier development of green finance have been actively exploring new green financial tools and have achieved certain results, so countries should continue to combine their own market demand and the characteristics of the development of the green industry to develop diversified financial products and services to provide more comprehensive green projects. Therefore, countries should continue to develop diversified financial products and services in line with their own market demand and the characteristics of green industry development to provide more comprehensive financing support for green projects.

8 Research limitations and future prospects

There are several limitations in this paper, which may provide directions for future research. First, this study mainly explores the impact of China's green finance reform and innovation pilot zone policies on total factor carbon productivity at the municipal level but lacks an exploration at the microlevel, such as the enterprise level. Second, this study also discusses the pathways through which green finance reform and innovation pilot zone policies enhance total factor carbon productivity, with particular emphasis on the mediating effects of green innovation levels and the ecological industrial structure, as well as the moderating effects of public environmental concern. Future research should explore more impact mechanisms, broaden the research horizon, and discuss the applicability of the findings at the micro 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

YZ: Writing – review and editing. RB: Writing – original draft. YL: Writing – review and editing. JW: Writing – review and editing. JZ: Writing – review and editing, Supervision.

Funding

The authors declare that financial support was received for the research and/or publication of this article. This research is supported by

the Shaanxi Province Soft Science Research Program Project, "Research on the Influence Mechanism of the Digital Economy on the Transformation and Upgrading of the Traditional Manufacturing Industry in Shaanxi Province and its Enhancement Path" (2024ZC-YBXM-090); the Xi'an Social Science Planning Fund Project "Xi'an Advanced Manufacturing Industry high-quality development level Comprehensive evaluation and improvement path Research" (23JX129); the Shaanxi Provincial Social Science Fund Project "Mechanism, Effect and Policy Research on the Digital Economy Driving Transformation and Upgrading of the Traditional Manufacturing Industry in Shaanxi" (2023D044); and the Research on the Impact of the Digital Economy on the Transformation and Upgrading of the Traditional Manufacturing Industry in Shaanxi Province (YCS23214337), funded by the Graduate Innovation and Practical Ability Training Program of Xi'an Shiyou University; and the National Social Science Foundation of China Western Project "Mechanism, Effect and Policy Research on the Impact of Labour Force Differentiation on Ecological Co-prosperity in Western Counties" (24XJY025).

Acknowledgements

We acknowledge all the researchers and participants of this study.

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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