

Environmental risk and corporate behaviour

Edited by

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Environmental risk and corporate behaviour

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International environmental regulation, trade liberalization, and enterprise pollution reduction: Evidence from China

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Regarding the signing of the China–ASEAN Free Trade Agreement (CAFTA) as a quasi-natural experiment, this article uses the difference-in-differences model to examine the pollution emissions of domestic trading enterprises in the face of varying trade openness under international environmental regulations. It is found that trade liberalization will drive domestic trading firms to choose more proactive pollution abatement strategies, namely, the signing of CAFTA facilitates pollution reduction in enterprises trading mainly with CAFTA members. This effect is more significant in non-state-owned enterprises and labor-intensive enterprises. In particular, the effect of becoming a member of CAFTA to facilitate firm-level pollution reduction has a time lag, and its marginal effect tends to expand over time.

KEYWORDS

trade liberalization, environmental regulation, pollution emissions, CAFTA, difference-in-differences method

Introduction

The earth is experiencing major changes in global and regional climates (Dodd and Douhovnikoff, 2016), and it is predicted that these changes will exert a significant impact on both human well-being and global sustainability (Huang et al., 2021; Cai et al., 2022). Government across the world has formulated and implemented a large number of environmental regulations with different jurisdictions to coordinate the contradiction between domestic economic growth and environmental protection (Liu et al., 2022). Specifically, in the context of free trade and economic globalization, many countries have raised the operating environment standards of their domestic markets, refusing to allow the products that ignore environmental pollution reduction to enter their domestic markets. This kind of international environmental regulation has evolved into an important part of competition rules or environmental barriers that hinder trade liberalization, leading to profound changes in the way enterprises operate.

Confronted with increasingly stringent environment/green trade barriers, there have been many debates on their impacts on international trade. Some studies suggested that due to stricter environmental regulations, the corresponding exports of heavy industries will be reduced (Merican et al., 2007; Cole et al., 2011; Ghani, 2012). Cole et al. (2010) reached a similar conclusion and showed that environmental regulation was an important determinant of Japan's status as a net importer in non-OECD countries and China. However, another branch of the literature found that environmental regulation does not always have a negative impact on international trade; instead, stricter environmental standards can facilitate the transition to cleaner production processes in developing countries (Arouri et al., 2012).

In view of the existing environmental regulation literature in an open economy, however, it seems that most studies are confined to economic activities, whereas less attention has been paid to enterprises' environment practices. In fact, in the recent years, developed economies, including countries in the European Union (EU), the United States, and Japan, have been the earliest, most frequent, and strictest countries and regions in adopting environmental regulation measures in the field of international trade, mainly by "improving environmental standards," "increasing inspection and quarantine items," and making "changes in technical regulations," which prompted trading enterprises of developing countries (e.g., China and Vietnam) to continue to implement ISO9000 and other environmental or technology standards of certification. In this background, it is reasonable to infer that not only will trade performance change, but pollution reduction will also be directly affected. Therefore, this article attempts to shed light on the question of how trade liberalization affects the environment practices of trading enterprises in the context of increasingly stringent international environmental regulations.

Under the constraints of the international market for environmental standards, domestic trading enterprises may try to attach green attributes to their products to meet basic transaction conditions and expand their international market share (Bagnoli and Watts, 2003), thus benefiting from more efficient utilization of materials and energy. Furthermore, in the context of responsible consumption, as consumers are willing to pay additional fees for the products of socially responsible enterprises (Kotler and Lee, 2005; Leisinger, 2005; McWilliams et al., 2006), domestic trading enterprises may improve the production environment standards to increase the resolution with similar products and obtain new market segments (such as "green" consumers) (Hart, 1995; Russo and Fouts, 1997; Kramer and Porter, 2011; Oikonomou et al., 2014). Based on the above mechanism, Costantini and Mazzanti (2012) found that EU environmental regulation can promote enterprise innovation and significantly increase exports of various industries. Fernández-Kranz and Santaló (2010) and Flammer (2015) proved that intensification of

market competition can improve firm-level environmental performance and that trade liberalization is an important factor in shaping the practice of enterprise emission reduction.

Enterprises respond to trade liberalization by reducing pollution emissions, so that they can stand out in the competition with rivals, which supports the view of the Porter hypothesis.¹ However, international environmental policies exert environmental pressure on enterprises. Controlling pollution or updating equipment is bound to occupy the original production management and technological innovation resources, which will have adverse impacts on the productivity and trade competitiveness of enterprises (Copeland and Taylor, 2004). Specifically, in emerging economies with relatively low per capita income (e.g., China, India, and Brazil), consumers are highly price-sensitive, and therefore, trading enterprises' implementation of a "green" differentiation strategy may become a risky choice (Biswas and Roy, 2015). Bansal and Roth (2000) found that Japanese and British companies only consider environmental protection measures when improving their financial performance. Orsato (2006) showed that the lack of reliable information on product environmental performance is the main obstacle to consumers' willingness to pay, which weakens the willingness of enterprises to "go green." Therefore, due to cost pressure considerations and the uncertainty of green consumption awareness of target consumers, domestic trading enterprises may not implement emission reduction in response to international environmental regulation under the free trade system.

Based on the above practical observation and theoretical analysis, this study conducts a quasi-natural experiment in the form of the China-ASEAN Free Trade Agreement (CAFTA), which was signed in 2002 and entered into force in 2005, to empirically test the effect of trade liberalization on the green development of China's trading enterprises by employing the difference-in-differences (DID) method. We find that China's trading enterprises respond to higher competitive pressure from trade liberalization by reducing their pollution emissions under the increasingly strict conditions of environmental protection in production and trade. In an auxiliary analysis, this article documents that this effect is stronger for non-state-owned enterprises (non-SOEs) and labor-intensive enterprises. The comparative advantage of developing countries' products mainly comes from low factor prices, and the international environmental standards aimed at protecting the environment and enhancing social welfare may seriously weaken the international competitiveness of labor-intensive industries, such as electronics, clothing, toys, textiles, and shoes, forcing trading enterprises, especially private enterprises without policy

1 Porter and Van der Linde (1995) proposed that well-designed environmental regulations can protect the environment and accelerate technology innovation, offsetting compliance costs, which is known as the Porter hypothesis.

support, to reduce pollution to meet trading standards. Consequently, the survival risk of trading enterprises in developing countries will be increased significantly. From the perspective of dynamic effect, the positive effect of membership of CAFTA on enterprise pollution reduction has a time lag, and its marginal effect shows an expanding trend with the passage of time.

The contributions of this article are as follows. First, while the existing literature primarily examines the policy effects of international environmental regulation on import and export activities (Merican et al., 2007; Cole et al., 2011; Aroui et al., 2012; Ghani, 2012), less attention has been paid to how domestic trading enterprises respond to it in terms of pollution reduction. Second, unlike previous studies that focus on the environmental pollution performance of general enterprises (Duanmu et al., 2018), this article investigates the environmental practices of domestic trading enterprises when facing drastic trade liberalization. Third, this article extends the related research studies (Fernández-Kranz and Santaló, 2010; Flammer, 2015) and considers the issue of enterprises' pollution reduction in the context of emerging economics or developing countries, improving the applicability and universality of the conclusions of previous research.

The remainder of this article is organized as follows. See the section "Theoretical analysis and research hypothesis" outlines the establishment of an international oligopoly model for theoretical analysis. See the section "Sample and research design" describes the construction of the sample, variable measurement, and research design. The empirical analysis is presented in the section "Empirical results." Finally, see the section "Conclusion" summarizes the main conclusions.

Theoretical analysis and research hypothesis

Basic model

Following Brander and Spencer (1985) and Wang et al. (2012), we formulate an international duopolistic model composed of one domestic enterprise and one foreign enterprise, indexed by 0 and 1, respectively. Both enterprises export different products to a third country's market and engage in Cournot players. The linear (inverse) demand function is specified with $P_i = 1 - q_i - \gamma q_{-i}$, $i = 0, 1$, where q_i denotes the outputs of the firm. We assume that all firms use an identical technology and have increasing marginal cost function:

$$C(q_i) = \frac{1}{2} q_i^2.$$

Although the world's economic landscape is increasingly moving toward greater trade liberalization, tariffs still exist in most economies to protect domestic industries. Accordingly, it

is assumed that a uniform tariff rate $t \in (0, 1)$ is imposed on the foreign firm's output. The profits of two firms are given by:

$$\pi_i = P_i(1 - t)q_i - \frac{1}{2}q_i^2, i = 0, 1 \quad (1)$$

The production of commodities in both enterprises leads to pollution emissions. However, each enterprise can prevent pollution by adopting abatement measures to achieve the environmental standards of the host country. To simplify the analysis, we assume that only the domestic enterprise has concerns about the problem of emission reduction and chooses to produce environmentally friendly products. Following Goering (2007), the payoff of the domestic enterprise is to maximize the weighted sum of its own profits and the host country's consumer surplus:

$$V = \pi_0 + \alpha CS \quad (2)$$

where $CS = \frac{1}{2}(q_0^2 + q_1^2 + 2\gamma q_0 q_1)$ denotes the host country's consumer surplus. $\alpha \in [0, 1]$ captures the level of pollution reduction or the willingness to provide environmentally friendly products to the host country. Specifically, as α increases, the domestic enterprise makes more effort to meet environmental standards and provide environmentally friendly products in the host country market.

A two-stage game is constructed. In stage 1, the domestic trading enterprise chooses the optimal environmental practice in the host country (α). In stage 2, all the enterprises choose their output levels according to the Cournot equilibrium to maximize their respective objectives. We solve the game through backward induction.

Analytical results

In the last stage of the game, given α and t , the domestic trading enterprise chooses q_0 to maximize (2) and the foreign trading enterprise chooses q_1 to maximize (1). The first-order conditions are as follows, respectively:

$$\frac{\partial V}{\partial q_0} = 1 - t + (2t + \alpha - 3)q_0 + (t + \alpha - 1)\gamma q_1 = 0 \quad (3)$$

$$\frac{\partial \pi_1}{\partial q_1} = (1 - t)(1 - \gamma q_0) - (3 - 2t)q_1 = 0 \quad (4)$$

Considering Eqs. 3, 4 simultaneously, we obtain the equilibrium outputs:

$$\begin{aligned} q_0^* &= \frac{(1-t)[3-2t-(1-t-\alpha)\gamma]}{(3-2t)(3-2t-\alpha)-(1-t)(1-t-\alpha)\gamma^2} \\ q_1^* &= \frac{(1-t)[3-\alpha-t(2-\gamma)-\gamma]}{(3-2t)(3-2t-\alpha)-(1-t)(1-t-\alpha)\gamma^2} \end{aligned} \quad (5)$$

Using q_0^* and q_1^* , we calculate the following equilibrium outcomes:

$$\begin{aligned}
 P_0^* &= \frac{(3-2t)(2-t-\alpha)-(2-t)(1-t)\gamma+(1-t)\alpha\gamma^2}{(3-2t)(3-2t-\alpha)-(1-t)(1-t-\alpha)\gamma^2} \\
 P_1^* &= \frac{(2-t)[3-\alpha-t(2-\gamma)-\gamma]}{(3-2t)(3-2t-\alpha)-(1-t)(1-t-\alpha)\gamma^2} \\
 \pi_0^* &= \frac{(1-t)^2[3-2t-(1-t-\alpha)\gamma]\{4t(t+\alpha-3)+[t(5-2t)-\alpha]\gamma+2(1-t)\alpha\gamma^2+3(3-2\alpha-\gamma)\}}{2[(3-2t)(3-2t-\alpha)-(1-t)(1-t-\alpha)\gamma^2]^2} \\
 \pi_1^* &= \frac{(1-t)^2(3-2t)[3-\alpha-t(2-\gamma)-\gamma]^2}{2[(3-2t)(3-2t-\alpha)-(1-t)(1-t-\alpha)\gamma^2]^2} \\
 CS^* &= \frac{(1-t)^2(1+\gamma)(18-24t+8t^2-6\alpha+4t\alpha+\alpha^2-(2-2t-\alpha)(6-4t-\alpha)\gamma+2(1-t)(1-t-\alpha)\gamma^2)}{2[(3-2t)(3-2t-\alpha)-(1-t)(1-t-\alpha)\gamma^2]^2} \quad (6)
 \end{aligned}$$

Note that $\pi_0^* \geq 0$ requires $0 \leq \gamma \leq 1$, $0 < t \leq \tilde{t}$, $0 \leq \alpha \leq 1$ or $0 \leq \gamma \leq 1$, $\tilde{t} < t < 1$, $0 \leq \alpha \leq \tilde{\alpha}^2$, which is assumed in the following discussion. Differentiating q_0^* and q_1^* with respect to α , it is easy to see that when the domestic trading enterprise gradually implements relatively positive environmentally responsible strategies in the host country, it will acquire a greater market share than the foreign trading enterprise ($\frac{\partial q_0^*}{\partial \alpha} > 0$, $\frac{\partial q_1^*}{\partial \alpha} < 0$). This result means that the domestic trading enterprise can improve its competitiveness and differentiate itself from the foreign rival, which conforms to economic practical experience that the host country (or consumers) is always willing to import (purchase) products from environmentally responsible enterprises.

In the first stage, given the above equilibrium outcomes, the domestic trading enterprise chooses the optimal level of pollution reduction or the willingness to provide environmentally friendly products to the host country. Following the general oligopoly literature, the objective of the domestic enterprise is to choose α to maximize its own profits. Combined with the derivatives ($\frac{\partial \pi_0^*}{\partial \alpha} = 0$, $\frac{\partial^2 \pi_0^*}{\partial \alpha^2} < 0$), we can obtain only one interior and positive solution:

$$\alpha^* = \frac{3\gamma^2 - 8t\gamma^2 + 7t^2\gamma^2 - 2t^3\gamma^2 - \gamma^3 + 3t\gamma^3 - 3t^2\gamma^3 + t^3\gamma^3}{9 - 12t + 4t^2 + 6\gamma - 7t\gamma + 2t^2\gamma - 3\gamma^2 + 5t\gamma^2 - 2t^2\gamma^2 - \gamma^3 + 2t\gamma^3 - t^2\gamma^3} \quad (7)$$

In general, tariff reductions represent greater trade liberalization. Therefore, to further explore the impact of trade liberalization on the optimal environmental decision-making of domestic trading enterprises, we differentiate α^* with

respect to t and find $\frac{\partial \alpha^*}{\partial t} < 0$. This result shows that α^* is the subtractive function of t , that is, with the deepening of trade liberalization, the domestic trading enterprise will adopt more environmentally responsible measures to engage in production activities to cultivate international competitive advantage. Accordingly, we formulate the following research hypothesis:

Hypothesis 1: Under stringent international environmental protection standards, domestic trading enterprises will choose more proactive pollution emission reduction strategies to maintain market competitive advantage. In brief, trade liberalization will drive trading enterprises to reduce pollution emissions.

Sample and research design

The theoretical analysis shows that domestic trading enterprises will choose more proactive pollution abatement strategies to maintain their competitiveness in the international market if there is a tendency toward a more open trading environment. Are these firms really responding in this way? If so, how significant is this effect? To answer these questions, the primary task is to determine how to measure the variation in trade openness. In general, the measure of trade openness tends to be tariffs; however, the change in a country's tariff policy is discrete in time, the adjustment direction is not uniform, each adjustment involves a wide variety of commodities, and therefore, there are certain difficulties in operation.

With the deepening of China's economic and trade relations with the world, actively promoting the negotiation of Free Trade Agreements (FTAs) has become an important part of China's new round of the opening-up strategy. After signing FTAs, the contracting countries often reduce tariffs substantially, or even achieve zero tariffs, which provides us with an exogenous shock to measure the tariff changes. However, by 2018, China had signed 16 FTAs involving 24 countries or regions in Asia, Oceania, Latin America, and Europe, including China-Maldives, China-Georgia, China-Australia, China-South Korea, China-Switzerland, China-Iceland, China-Costa Rica, China-Peru, China-Singapore, China-New Zealand, China-Chile, China-Pakistan, and China-ASEAN. Of these FTAs, only CAFTA is a collective agreement signed by China with a number of developed and developing countries simultaneously, which provides us with more abundant and more general research samples. Therefore, using China's membership of CAFTA as an opportunity to measure the variation in trade openness,³ this article examines

² $\tilde{t} = \frac{9-5\gamma+2\gamma^2}{4(2-\gamma)} - \frac{1}{4} \sqrt{\frac{16+8\gamma-7\gamma^2-4\gamma^3+4\gamma^4}{(2-\gamma)^2}}$, $\tilde{\alpha} = \frac{9-12t+4t^2-3\gamma+5t\gamma-2t^2\gamma}{6-4t+\gamma-2\gamma^2+2t\gamma^2}$

³ As a new round of opening-up strategy, the negotiation of Free Trade Agreements (FTAs) is always accompanied by the reduction both for tariff and non-tariff barriers among the contracting parties. Thus, it is reasonable to choose the accession to FTA as a proxy for gauging trade openness, and compared with tariff, this measure is more comprehensive and extensive.

the impact of membership of CAFTA on the domestic firm-level pollution reduction.

Design

In general, the impact of CAFTA on enterprises' pollution emissions can be assessed by making a horizontal and vertical comparison. Horizontal comparison shows the differences in pollution emissions between firms that trade mainly with CAFTA members and those that do not; however, it ignores the heterogeneity between firms. The latter is a direct comparison of the differences in pollution emissions of enterprises trading mainly with CAFTA members before and after becoming a member of CAFTA; however, it does not take into account the consistency of time trends. Following the general practice in environmental regulation literature (Chen et al., 2018; Wang et al., 2019), we regard the membership of CAFTA as a quasi-natural experiment.⁴ Due to its application at different enterprises at the same time (trade and non-trade or major and non-major trade), we divide Chinese enterprises into two groups: the treatment group and the control group. The treatment group contains the enterprises significantly affected by membership of CAFTA, and the control group contains the enterprises minimally affected by membership of CAFTA. This allows us to adopt the DID method to explore the effects of varying intensity of trade liberalization caused by becoming a member of CAFTA on firm-level pollution emissions:

$$Y_{it} = \alpha_i + \beta_1 treat_i + \beta_2 post_t + \beta_3 treat_i * post_t + \beta_4 Control_{it} + \mu_n + \vartheta_j + \varepsilon_{it}$$

where the subscripts i and t represent the enterprise and year, respectively. Y_{it} represents the level of pollution emissions of firm i in year t . To enhance the reliability and robustness of the research results, we choose both water pollution (*wastewater*) and air pollution (*wasteair*) as a measure of pollution emissions, expressed as the natural logarithm of the total amount of industrial wastewater/waste gas discharged by enterprises, respectively.

$treat_i$ is the grouping variable to identify whether enterprise i belongs to the treatment or control group. A total of eleven countries have become the members of CAFTA: China, Malaysia, Indonesia, Thailand, the Philippines, Singapore, Brunei, Vietnam, Laos, Myanmar, and Cambodia. Unlike the

previous studies that simply classify the group based on the occurrence of the trade, we aim to distinguish the treatment group from the control group to a greater extent and avoid as far as possible the interactive effects on the control group as a result of becoming a member of CAFTA. If an enterprise's share of trade (exports or imports) with the above-mentioned countries is larger than the median of that of all enterprises in all years, it trades mainly with CAFTA members and belongs to the treatment group, whereas if an enterprise has neither import nor export trade with the above-mentioned countries, it belongs to the control group.

$post_t$ is the time difference variable before and after the signing of CAFTA to recognize the period in which enterprise i is located. Although the relevant agreement between China and ASEAN was formally signed in November 2002, the tax reduction of CAFTA was not initiated until July 2005, which was objectively the point when the agreement came into effect. Therefore, 2005 is adopted as the starting year when China's membership of CAFTA has an effect on enterprises' pollution emissions, with $post_t$ taking a value of 0 before 2005 and 1 after 2005.

According to the different values assigned to $treat_i$ and $post_t$, all samples can be divided into the following four groups: the treatment group before the signing of CAFTA ($treat_i=1, post_t=0$), the treatment group after the signing of CAFTA ($treat_i=1, post_t=1$), the control group before the signing of CAFTA ($treat_i=0, post_t=0$), and the control group after the signing of CAFTA ($treat_i=0, post_t=1$). The net policy shock effect, measured by the characterization of the regression coefficient of the interaction term $treat_i * post_t$, can be obtained through two different calculations of the above four groups of samples. Thus, $treat_i * post_t$ is the core explanatory variable, whose regression coefficient $\beta_3 > 0$ means that the pollution emissions of the treatment group increase compared to those of the control group and membership of CAFTA has a negative impact on the enterprise pollution reduction, whereas $\beta_3 < 0$ denotes that the pollution emissions of the treatment group decrease compared to those of the control group and membership of CAFTA has a positive impact on the enterprise pollution reduction.

Following the approach of existing studies (Flammer, 2015; Duanmu et al., 2018), we include control variables as follows: (1) enterprise scale (*size*), measured as the natural logarithm of its net fixed assets; (2) enterprise age (*age*), measured by adding 1 to the difference between the year in which the enterprise is located and founded; (3) capital intensity (*intz*), measured by the ratio of the average balance of net fixed assets to the number of employees; (4) asset-liability ratio (*debt*), measured by the ratio of total liabilities to total assets; (5) enterprise profitability (*profit*), measured by the ratio of operating profit to sales revenue; And (6) asset liquidity (*liquidity*), measured by the ratio of the excess of current assets over current liabilities to current assets. Furthermore, μ_n and ϑ_j are industrial effects and regional effects, respectively, and ε_{it} is a random disturbance term.

⁴ A quasi-natural experiment means that experimental treatment level is completely independent of individual characteristics or other factors that might affect the results of the experiment, thus largely avoiding omitted variable bias and endogeneity bias. Hence, compared with traditional OLS or panel fixed effect estimation, DID model can better identify the causal effect between explained variable and explanatory variable.

Sample

The sample for this article is mainly taken from the Database of Chinese Industrial Firms and the Database of Chinese Customs Firms from 2000 to 2009. A different treatment for the two databases is designed to improve the accuracy of this empirical study, processing the monthly data of products on the Database of Chinese Customs Firms by adding it to annual data. Moreover, the following treatments are carried out on the Database of Chinese Industrial Firms consecutively. First, samples with fewer than eight employees are excluded based on the experiences of Brandt et al. (2012) and Yu (2014). Second, samples that do not conform to objective facts and have excess missing data and outliers (e.g., total output less than zero) are excluded. Third, samples that are not in correspondence with the accounting standards (e.g., total assets less than current assets or fixed assets) are not available. In addition, we exclude samples with errors and omissions in their original records (e.g., the enterprise has been operating for less than 1 month or more than 12 months).

Due to the difference in the coding system between the Database of Chinese Industrial Firms and the Database of Chinese Customs Firms – the former has a 10-digit legal person code and the latter has a 9-digit code – this article draws on Yu and Tian's (2012) article to combine enterprises with the same name and year in these two databases while excluding samples that do not record industrial wastewater (waste gas) emissions. Based this, enterprises that exited the market before 2005 and those that entered the market after 2005 will be excluded to ensure that all firms we choose are still in operation in the policy year of 2005. Continuous variables used in the regressions are winsorized at 1% to mitigate the possible effects of outliers, resulting in 33,229 initial observations. Descriptive statistics for the main variables are shown in Table 1.

Empirical results

Parallel trend test

The DID method is valid on the premise of meeting the parallel trends assumption that the growth rate of the dependent variable should be consistent in the treatment and control groups before and after treatment. Figures 1, 2 show that the total industrial wastewater (waste gas) emissions of the treatment and control groups maintain a highly similar trend prior to China becoming a member of CAFTA, both being on a slow rise. After China became a member of CAFTA, the trends in the two groups diverge significantly. In terms of total industrial wastewater discharge, the curve for the control group rises

slowly and then falls, whereas that of the treatment group remains virtually constant at first and then plunges. For total industrial waste gas emissions, both groups show a continuing downward trend, with a larger decline in the treatment group. The above findings prove that the DID model meets the prerequisites of the common trend assumption in temporal trends.

Baseline regression results

The baseline regression results regarding the effect of membership of CAFTA on enterprise pollution emissions are presented in Table 2. As shown in columns (1) and (2), the coefficients of *treat*post* are significant and negative. After adding control variables in columns (3) and (4), the coefficients are still significantly negative. This indicates that the total industrial wastewater (waste gas) emissions of enterprises that trade mainly with CAFTA members decreased more significantly after China becomes a member of CAFTA, signifying that CAFTA strongly encourages trading enterprises to work on pollution control and compete in international markets with products and services that are highly socially responsible. Thus, hypothesis 1 is valid.

Regarding the control variables, the regression coefficients of *size*, *age*, and *intz* are positive, and most of them pass the 1% significance test, which indicates that the enterprise emits more pollution with larger size, longer survival, and higher capital intensity. This may be related to the corporation organizational inertia. The regression coefficients of *profit*, *debt*, and *liquidity* are negative, and most of them pass the 1% significance test. This suggests that the enterprise emits less pollution with greater profitability and liquidity. The findings are in line with those of previous research indicating that successful pollution control relies on good financial performance. In particular, enterprise pollution emissions decrease with the increase in debt to total assets ratio, probably due to the fact that the enterprise purchases major equipment for pollution control, which generally raises the gearing overall but also achieves pollution reduction.

TABLE 1 Descriptive statistics of variables.

Variables	Mean	SD	Min	Max
wastewater	10.84	2.05	5.54	15.82
wasteair	7.77	2.20	2.56	13.73
size	11.48	1.44	8.62	15.39
age	14.82	12.80	2.00	67.00
intz	155.23	243.74	1.98	1586.51
debt	0.56	0.25	0.03	1.28
profit	0.03	0.10	−0.44	0.32
liquidity	−0.01	0.71	−3.62	0.97

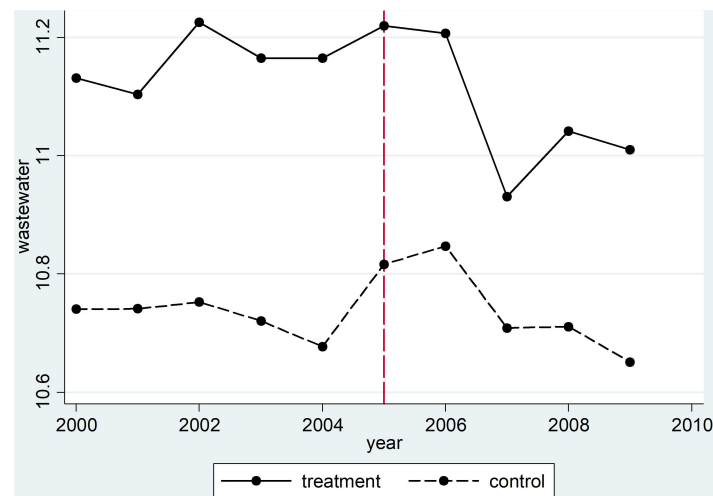


FIGURE 1
Parallel trend of wastewater.

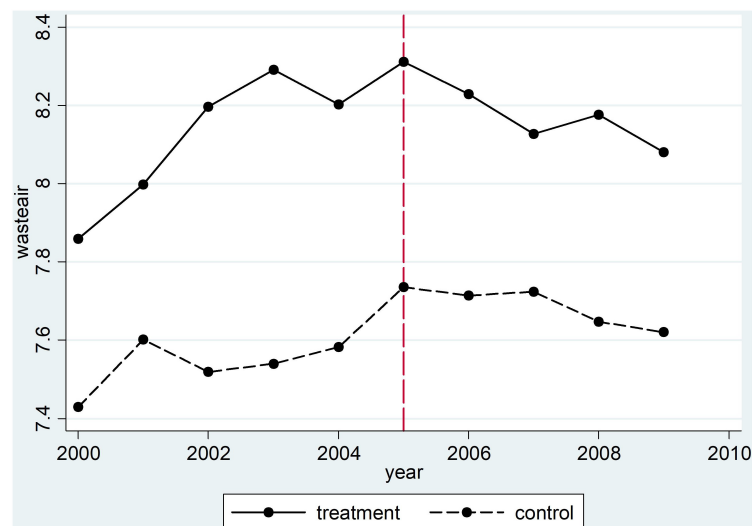


FIGURE 2
Parallel trend of wastear.

Heterogeneity analysis

Enterprises with different ownership types

There are differences between SOEs and non-SOEs in terms of their business objectives, clearly subjected to government intervention, are inherently required to assume social responsibilities, external environment, and operating method. Due to the special political and social attributes, SOEs, clearly subjected to government intervention, are inherently required to assume social responsibilities, such as environmental cleanup. Therefore, clearly subjected to

government intervention, are inherently required to assume social responsibilities, the pollution emission of non-SOEs may be more influenced by market mechanisms than that of SOEs. Accordingly, we divide all the enterprises into SOEs and non-SOEs to assess the impact of membership of CAFTA on the pollution reduction of enterprises with different ownership types. The estimation results are shown in [Table 3](#), where columns (1) and (2) are regression results for the SOEs and columns (3) and (4) are those for the non-SOEs.

We found that the estimated coefficients of the interaction terms, *treat*post*, in columns (1) and (2) are negative but statistically insignificant while those in columns (3) and (4) are

negative and pass the 5 and 10% significance tests, respectively. It can be concluded that the estimation results of non-SOEs are more consistent with the whole sample than those of SOEs and that membership of CAFTA leads to greater improvement in non-SOEs' pollution reduction. This is also in line with the current situation of Chinese enterprises. Compared to SOEs, naturally profit-seeking non-SOEs are more likely to follow the market mechanism and adjust their production and operation despite facing intense pressure from stakeholders and improve their pollution control to maintain or enhance their competitiveness in an increasingly fierce game. Even if China has greater openness, the competitive advantage of SOEs, which dominate national economic development and safeguard people's well-being, will not decline sharply in the near future since they are monopolies or oligopolies. In particular, SOEs have been driven by the government to improve their pollution control, and the higher openness by becoming a member of CAFTA may have not led to obvious stimulation or pressure on them.

TABLE 2 Baseline regression results.

Variables	(1)	(2)	(3)	(4)
	<i>wastewater</i>	<i>wastewater</i>	<i>wastewater</i>	<i>wastewater</i>
<i>treat*post</i>	−0.15*** (−3.00)	−0.15*** (−2.69)	−0.10** (−2.34)	−0.11** (−2.11)
<i>treat</i>	0.44*** (11.05)	0.56*** (12.33)	0.07** (2.09)	0.17*** (4.29)
<i>post</i>	0.08*** (3.26)	0.23*** (8.24)	−0.19*** (−8.82)	−0.10*** (−4.05)
<i>size</i>			0.66*** (77.01)	0.70*** (66.25)
<i>age</i>			0.02*** (22.93)	0.01*** (11.93)
<i>intz</i>			0.00005 (1.03)	0.0006*** (9.48)
<i>profit</i>			−1.32*** (−12.48)	−1.14*** (−8.33)
<i>debt</i>			−0.30*** (−6.14)	−0.10* (−1.69)
<i>liquidity</i>			−0.18*** (−10.69)	−0.14*** (−7.43)
Constant Term	12.19*** (19.63)	8.99*** (13.16)	2.13*** (3.15)	−1.36** (−2.13)
Industrial Effects	Y	Y	Y	Y
Regional Effects	Y	Y	Y	Y
Observation	30284	23633	27425	21436
R ²	0.29	0.32	0.45	0.48

Values in brackets are t-statistic. *, **, and *** denote 10, 5, and 1% significance levels, respectively, with the same subscripts. Y denotes "Yes."

TABLE 3 Regression results of subsamples by enterprise ownership.

Types	SOEs		non-SOEs	
Variables	(1)	(2)	(3)	(4)
	<i>wastewater</i>	<i>wastewater</i>	<i>wastewater</i>	<i>wastewater</i>
<i>treat*post</i>	−0.04 (−0.25)	−0.10 (−0.63)	−0.09** (−2.00)	−0.10* (−1.78)
<i>treat</i>	0.22** (2.43)	0.29*** (2.76)	0.08** (2.21)	0.17*** (3.98)
<i>post</i>	−0.56*** (−7.90)	−0.32*** (−3.93)	−0.13*** (−5.81)	−0.06** (−2.27)
<i>size</i>	0.80*** (29.35)	0.85*** (22.35)	0.64*** (70.24)	0.67*** (59.99)
<i>age</i>	0.01*** (4.93)	0.01*** (3.48)	0.02*** (16.70)	0.01*** (7.75)
<i>intz</i>	−0.0004*** (−2.68)	0.0005*** (2.64)	0.0001** (2.13)	0.0006*** (8.96)
<i>profit</i>	−1.55*** (−4.74)	−1.33*** (−3.00)	−1.25*** (−11.24)	−1.07*** (−7.31)
<i>debt</i>	−0.20 (−1.19)	0.25 (1.14)	−0.28*** (−5.46)	−0.12* (−1.95)
<i>liquidity</i>	−0.25*** (−4.24)	−0.16** (−2.36)	−0.17*** (−9.85)	−0.13*** (−6.89)
Constant Term	0.25 (0.27)	−2.75*** (−2.64)	4.34*** (10.88)	−1.83*** (−4.62)
Industrial Effects	Y	Y	Y	Y
Regional Effects	Y	Y	Y	Y
Observation	2411	2110	24948	19256
R ²	0.59	0.65	0.44	0.44

Values in brackets are t-statistic. *, **, and *** denote 10, 5, and 1% significance levels, respectively, with the same subscripts. Y denotes "Yes."

Enterprises in different industries

Given the factor intensity of different industries, this article classifies all the enterprises into labor-intensive enterprises and capital- and technology-intensive enterprises to discuss the impact of membership of CAFTA on pollution reduction in different industries.⁵ The results are shown in Table 4, where columns (1) and (2) are regression results for the labor-intensive enterprises and columns (3) and (4) are those for the capital- and technology-intensive enterprises. We found that the regressions for the subsamples by industry

⁵ According to the three-digit industry codes in the Database of Chinese Industrial Firms, capital- and technology-intensive enterprises include the petroleum processing and coking, and nuclear fuel processing industry; non-metallic mineral products industry; ferrous metal smelting and rolling processing industry; non-ferrous metal smelting and rolling processing industry; metal products industry; general equipment manufacturing; special equipment manufacturing; transportation equipment manufacturing; electrical machinery and equipment manufacturing; instrumental, cultural and official machinery manufacturing; chemical fiber manufacturing; pharmaceutical manufacturing; and chemical raw materials and chemical products manufacturing. The remainder are labor-intensive enterprises.

yield negative coefficients for the interaction terms, but only the samples of labor-intensive enterprises with total industrial wastewater emissions as the explained variable pass the 5% significance test. This suggests that China's membership of CAFTA helps labor-intensive enterprises with pollution control of waste gas to a greater extent than capital- and technology-intensive enterprises. On the one hand, the products that China sells to ASEAN countries are mainly low-price labor-intensive products, such as clothing textiles, fresh oil, frozen fish, and other kinds of agroforestry by-products, so membership of CAFTA has a greater influence on the labor-intensive industries. On the other hand, most of the research samples are from manufacturing sectors, where most capital- and technology-intensive enterprises, still at the startup stage in China, are classified as energy-intensive industries where there is a threshold for environmental investment and a higher cost of pollution control than for labor-intensive enterprises. This

huge cost may deter these enterprises even though CAFTA has increased international competition.

Dynamic marginal effects

Since the variable *post* is assigned a value of 1 in 2005 and beyond, the baseline regression measures the difference in the average level of enterprise emissions before and after China became a member of CAFTA (2000–2004 and 2006–2009), which does not reflect whether there is a time lag and stability in the effect of this public policy. Accordingly, Eq. 8 is extended with a triple interaction term comprising the time dummy variable and *treat*post*:

$$Y_{it} = \alpha_i + \alpha_3 \text{treat}_i + \alpha_4 \text{post}_t + \sum_{\tau=0}^2 \alpha_{\tau} \text{DiD}_{-\tau} * \text{treat}_i * \text{post}_t + \alpha_5 \text{Control}_{it} + \mu_n + \vartheta_j + \varepsilon_{it}$$

where *DiD*– τ is the dummy variable for the year during the period after China became a member of CAFTA, and *DiD*– τ is assigned a value of 1 when the firm is in period τ , otherwise a value of 0. In this article, the current period of China's membership CAFTA (namely, in 2005) is considered to be in period 0, the first 2 years after China became a member of CAFTA are seen as being in period 1, and the second 2 years are considered to be in period 2. The estimated coefficient α_{τ} is the key subject of examination for the dynamic marginal effects in period τ . The regression results with total industrial wastewater discharge and wastear emissions as explanatory variables are reported in **Tables 5, 6**, respectively. For the full sample in column (1), none of the coefficients of the triple interaction term *DiD*–0**treat*post* is significant, whereas both coefficients of *DiD*–1**treat*post* and *DiD*–2**treat*post* are significantly negative, and the absolute value of the latter is greater than that of the former. This proves that it does not work well on industrial wastewater (waste gas) reduction of enterprises in the period when CAFTA has just come into force, but gradually improves during periods 1 and 2, that is, there is a time lag in the effect of China becoming a member of CAFTA on enterprises' pollution reduction, and the marginal effect tends to expand over time.

A closer look at the samples grouped by ownership reveals significant differences in the dynamic marginal effects between SOEs and non-SOEs. Shown as the regression results for the samples from SOEs in column (2) that are consistent with the previous findings, the estimated coefficients of *DiD*– τ **treat*post* are statistically insignificant, indicating that there is no significant effect of China becoming a member of CAFTA on pollution

TABLE 4 Regression results of subsamples by industry.

Types	Labor-intensive enterprises		Capital- and technology-intensive enterprises	
Variables	(1)	(2)	(3)	(4)
	wastewater	wastear	wastewater	wastear
<i>treat*post</i>	–0.03 (–0.42)	–0.15** (–2.24)	–0.08 (–1.22)	–0.04 (–0.57)
<i>treat</i>	–0.04 (–0.78)	0.18*** (3.49)	0.06 (1.31)	0.15*** (2.67)
<i>post</i>	–0.10*** (–3.17)	0.01 (0.26)	–0.34*** (–10.00)	–0.23*** (–5.77)
<i>size</i>	0.65*** (52.93)	0.59*** (43.38)	0.74*** (56.89)	0.81*** (50.21)
<i>age</i>	0.01*** (7.66)	0.003** (2.53)	0.02*** (24.02)	0.01*** (11.35)
<i>intz</i>	0.0003*** (4.09)	0.0006*** (7.14)	–0.0001 (–1.39)	0.0005*** (6.10)
<i>profit</i>	–1.11*** (–6.89)	–0.72*** (–4.10)	–1.79*** (–11.47)	–1.45*** (–6.94)
<i>debt</i>	–0.26*** (–3.76)	–0.03 (–0.46)	–0.43*** (–5.38)	–0.18* (–1.87)
<i>liquidity</i>	–0.24*** (–10.42)	–0.09*** (–4.20)	–0.26*** (–8.74)	–0.19*** (–6.00)
Constant term	3.23*** (20.54)	0.62 (0.90)	2.08*** (3.25)	–3.73*** (–14.15)
Industrial effects	Y	Y	Y	Y
Regional effects	Y	Y	Y	Y
Observation	14779	11076	12646	10360
<i>R</i> ²	0.267	0.461	0.430	0.492

Values in brackets are t-statistic. *, **, and *** denote 10, 5, and 1% significance levels, respectively, with the same subscripts. Y denotes “Yes.”

TABLE 5 Dynamic marginal effects of total industrial wastewater emissions.

Types	Full sample	SOEs	non-SOEs	Labor-intensive enterprises	Capital- and technology-intensive enterprises
Variables	(1)	(2)	(3)	(4)	(5)
	<i>wastewater</i>	<i>wastewater</i>	<i>wastewater</i>	<i>wastewater</i>	<i>wastewater</i>
<i>DiD_0*treat*post</i>	0.04 (0.64)	0.07 (0.34)	0.04 (0.66)	0.13 (1.35)	0.09 (0.90)
<i>DiD_1*treat*post</i>	−0.10** (−2.04)	0.03 (0.17)	−0.09* (−1.68)	−0.04 (−0.51)	−0.10 (−1.22)
<i>DiD_2*treat*post</i>	−0.24*** (−3.90)	−0.29 (−1.34)	−0.22*** (−3.55)	−0.16* (−1.65)	−0.35*** (−3.80)
<i>treat</i>	0.07** (2.07)	0.22** (2.42)	0.08** (2.19)	−0.04 (−0.80)	0.15*** (3.02)
<i>post</i>	−0.19*** (−8.85)	−0.56*** (−7.93)	−0.13*** (−5.85)	−0.10*** (−3.18)	−0.34*** (−9.49)
Constant term	2.11*** (3.13)	0.21 (0.24)	4.32*** (10.82)	3.22*** (20.46)	2.08*** (13.02)
Controlled variable	Y	Y	Y	Y	Y
Industrial effects	Y	Y	Y	Y	Y
Regional effects	Y	Y	Y	Y	Y
Observation	27425	2411	24948	14779	12646
<i>R</i> ²	0.45	0.59	0.44	0.27	0.36

Values in brackets are t-statistic. *, **, and *** denote 10, 5, and 1% significance levels, respectively, with the same subscripts. Y denotes “Yes.”

TABLE 6 Dynamic marginal effects of total industrial wasteair emissions.

Types	Full sample	SOEs	Non-SOEs	Labor-intensive enterprises	Capital- and technology-intensive enterprises
Variables	(1)	(2)	(3)	(4)	(5)
	<i>wasteair</i>	<i>wasteair</i>	<i>wasteair</i>	<i>wasteair</i>	<i>wasteair</i>
<i>DiD_0*treat*post</i>	−0.01 (−0.10)	0.04 (0.20)	0.002 (0.02)	0.03 (0.33)	0.07 (0.59)
<i>DiD_1*treat*post</i>	−0.13** (−2.09)	−0.28 (−1.17)	−0.10 (−1.54)	−0.09 (−0.99)	−0.16 (−1.62)
<i>DiD_2*treat*post</i>	−0.17** (−2.41)	−0.05 (−0.16)	−0.19** (−2.51)	−0.24** (−2.22)	−0.25** (−2.12)
<i>treat</i>	0.17*** (4.28)	0.29*** (2.76)	0.17*** (3.97)	0.29*** (5.15)	0.14** (2.25)
<i>post</i>	−0.10*** (−4.07)	−0.32*** (−3.92)	−0.06** (−2.29)	−0.10*** (−2.71)	−0.16*** (−3.39)
Constant Term	−1.37** (−2.14)	−2.74*** (−2.63)	−1.84*** (−4.65)	0.003 (0.02)	−0.64*** (−2.83)
Controlled Variable	Y	Y	Y	Y	Y
Industrial Effects	Y	Y	Y	Y	Y
Regional Effects	Y	Y	Y	Y	Y
Observation	21436	2110	19256	11076	10360
<i>R</i> ²	0.48	0.65	0.44	0.31	0.33

Values in brackets are t-statistic. *, **, and *** denote 10, 5, and 1% significance levels, respectively, with the same subscripts. Y denotes “Yes.”

reduction by SOEs. Furthermore, the regression results in column (3) for the non-SOEs sample show that they are positive, negative, and negative, respectively, and the significance and absolute value increase period by period.

This suggests that the dynamic marginal effects of the samples of non-SOEs are essentially the same as those of the whole sample, that is, there is a time lag in the contribution of CAFTA to pollution abatement by non-SOEs

and, similarly, the marginal effect exhibits an expanding tendency over time.

In terms of the samples grouped by industry, we found that the dynamic marginal effects of labor-intensive enterprises are largely in parallel with those of capital- and technology-intensive enterprises. The estimated coefficients of $DiD\_ \tau^{treat*post}$ are shown as positive, negative, and negative, and they only pass the 5% significance test in period 2, indicating that there is a time lag of about 3–4 years in the effect of China becoming a member of CAFTA on the pollution reduction of enterprises in different industries.

Conclusion

International environmental regulation has evolved into a kind of “blue trade barrier,” which has become an important part of the competition rules in the international market. This article considers China becoming a member of CAFTA as a quasi-natural experiment and investigates the impact of trade openness on pollution abatement by enterprises with the DID method. We found that under international environmental regulation, the pollution abatement strategies of domestic trading firms are subjected to significant constraints from the international environment. Market competition intensifies in an increasingly open trading environment, and domestic trading enterprises will be proactive in strengthening pollution control in an effort to remain competitive in the host country. The empirical analysis reveals that enterprises trading mainly with CAFTA members are generally encouraged to reduce their pollution emissions after China became a member of CAFTA. China becoming a member of CAFTA motivates non-SOEs to fight pollution; however, it is not significant to SOEs. For the samples divided based on the capital intensity, it has a more significant positive effect on pollution reduction for labor-intensive enterprises than capital- and technology-intensive enterprises. In addition, there is a time lag in the effect of China becoming a member CAFTA on enterprises’ pollution reduction and a tendency for its marginal effect to expand over time, especially in the samples of non-SOEs.

At a time when the global environment is deteriorating, it is often used as a trading condition by multinational corporations to meet certain environmental standards. The conclusions of this article suggest that domestic trading enterprises should adopt proactive strategies, differentiating themselves from rivals through pollution control. By fully understanding the environmental culture of target countries, regions, and economies and weighing the cost of pollution control and the benefits of competition, efforts could

be made to merge into economic globalization. It is better to continue transforming and upgrading the manufacturing process flow and remain in alignment with international standards to enhance the competitive advantages of their products, as well as using relatively cleaner energy.

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

XC, QL, and QP contributed to the conception and design of the study. XC and QL organized the database and performed the statistical analysis. XC and QP wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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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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Can directors' and officers' liability insurance improve corporate ESG performance?

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Directors' and Officers' liability insurance (abbreviated as "D&O insurance") was born in the United States in the 1930s and has been widely used in Western countries. In contrast, China introduced D&O insurance in 2002, and its development has been relatively slow. With the revision and improvement of Chinese regulatory laws and regulations, such as the new Securities Law in March 2020, which further regulates the obligations and responsibilities of corporate management, and increases the penalties for information disclosure violations of listed companies, the risk to directors and executives performing their duties is promoted. This makes D&O insurance the focus of China's capital market, with huge potential for future development. Therefore, it is of urgent practical importance to study the impact of director liability insurance on corporate governance in China. At the same time, D&O insurance, as an effective risk management mechanism, has not yet reached a unified conclusion in the academic circles on its corporate governance effectiveness. On the one hand, D&O insurance may encourage directors and senior executives to be proactive to enhance the company's market value by taking risks, and on the other hand, it may induce opportunistic behavior of managers and reduce the company's value. Under the new development form, analyzing and researching the governance effect of D&O insurance from different angles will help to provide a theoretical basis for its further development and popularization in China's capital market. Thus, using a sample of Chinese A-share listed companies from 2011 to 2020, this study investigates the impact of D&O insurance on corporate ESG performance. The results show that D&O insurance significantly improves corporate ESG performance. Additional analysis suggests that the contribution of D&O insurance to ESG performance is achieved by improving independent director function-performing effectiveness and increasing corporate risk-taking. The findings of this paper have policy implications for a better understanding of the governance role of D&O insurance, encouraging companies to improve corporate ESG performance.

KEYWORDS

directors' and officers' liability insurance, ESG, independent director function-performing effectiveness, corporate risk-taking, economic policy uncertainty, industry competition

1 Introduction

Directors' and officers' (D&O) liability insurance is designed to protect the directors, supervisors, and senior management from personal liability that may stem from negligence or misconduct in the course of performing their regular duties (Lin et al., 2013; Aguir and Aguir 2020). D&O insurance has gained mature practice in developed countries. According to a survey by Tillinghast-Towers Perrin¹, 96% of U.S. companies and 88% of Canadian companies have purchased D&O insurance. In 2002, the China Securities Regulatory Commission issued the Code of Corporate Governance, which sets forth that listed companies can purchase D&O insurance for their directors and officers to protect their assets in the event of a lawsuit. However, as of November 2021, no more than 15% of listed companies in China have purchased D&O insurance. In 2020, the Luxin coffee's financial fraud incident broke out suddenly, and then it was revealed by investors that they had bought directors and executives with a large amount of D&O insurance. Whether the insurance can obtain claims and help investors recover losses has sparked a lot of discussions. D&O insurance has also received more attention from listed companies and academics as a result of Luxin Coffee.² With the establishment and improvement of the legal and capital market systems, D&O insurance has gradually gained popularity among emerging countries.

At the same time, with the gradual deterioration of the ecological environment and the acceleration of the global integration process, the world has shown an unprecedentedly high concern for sustainable development. The concept of sustainable development and corporate social responsibility has gained widespread public attention and recognition. As a systematic methodology to promote enterprise sustainability, ESG is a non-financial enterprise evaluation system focusing on the environment, society, and governance. It promotes enterprises to move from the pursuit of self-interest maximization to the pursuit of social value maximization, which is both a core framework and an inherent requirement for companies to pursue green development.

Using a sample of Chinese A-share listed companies from 2011 to 2020, this study investigates the impact of D&O insurance on corporate ESG performance. From a regression analysis of the data, followed by robustness tests, we reached the

following conclusions. D&O insurance significantly improves corporate ESG performance. Meanwhile, this positive relationship is affected by economic policy uncertainty and industry competition. Additional analysis suggests that the contribution of D&O insurance to ESG performance is achieved by improving independent director function-performing effectiveness and increasing corporate risk-taking.

This paper contributes to the literature in three ways. First, our study enriched the literature on the factors influencing corporate ESG performance. Previous studies mostly discuss this issue from the perspective of market, firm leadership, and ownership. Empirical studies focused on the insurance perspective are insufficient, our study takes D&O insurance as an example, which uncovers a new factor affecting corporate ESG performance and further enriches the literature on ESG performance. Second, our study provides a new perspective to study the consequences of D&O insurance. Extant literature on the governance function of D&O insurance tends to focus on the economic consequence of D&O insurance (Yuan et al., 2016; Wang et al., 2020). We, however, analyze the comprehensive governance consequences of D&O insurance from the perspective of ESG, expanding the research horizon of relevant literature. Third, our study revealed the transmission mechanisms of D&O insurance to ESG. It deepens the understanding of the relationship between D&O insurance and corporate ESG performance. Our study also provides practical guiding significance for management to improve ESG performance.

The remainder of this paper is organized as follows. The "Theoretical analysis and hypothesis developments" section develops our main hypotheses, "Literature review" combs through the related literature, the "Research Design" section refers to research design, and the "Empirical results" section presents the main empirical results and robustness tests. The "Additional analyses" section provides the intermediary mechanism tests. Finally, the "Conclusions and future perspective" section gives conclusions and policy suggestions.

2 Literature review

2.1 Theoretical hypotheses of D&O insurance

As one of the hedging tools for listed companies, D&O insurance can reduce the risk of directors, supervisors, and senior executives' practice, but also may cause a moral hazard to directors, supervisors, and senior executives, and damage the company's value.

Based on the external supervision hypothesis, scholars believe that director liability insurance can effectively play the role of third-party supervision of insurance companies, improve the level of corporate risk control, and thus enhance corporate performance (O'Sullivan, 2002; Yuan et al., 2016; Li and Xu, 2020). This is

¹ Towers Perrin is one of the world's largest global management and human resource consulting firms. Tillinghast—provides business management and actuarial consulting services to the insurance and financial industries, as well as risk management consulting services to a variety of public and private institutions.

² In April 2020, the fraud incident of Luxin Coffee suddenly broke out. Subsequently, investors discovered that Luxin Coffee had previously purchased D&O insurance with a large insured amount. Whether Luxin Coffee could get claims from the insurance company to help the majority of investors to recover part of the loss has become a hot topic of discussion for a while.

because insurance companies price premiums and assess risk based on a company's past credit and behavioral performance before underwriting. In underwriting, the insurer, as a stakeholder and independent external monitor, has the incentive and ability to externally monitor the manager's actions (Holderness, 1990), which helps to improve the level of corporate governance, reduce corporate agency costs and thus improve corporate performance (Ling, 2020). Based on the management incentive hypothesis, companies subscribe to D&O insurance initially to protect the private property of directors and officers from loss in the normal performance of their duties (Aguir and Aguir, 2020). Therefore, the subscription to D&O insurance can reduce the risk aversion and occupational risks of the insured managers (Hu and Hu, 2017), encourage the management to combine their interests with the interests of shareholders, stimulate the innovation enthusiasm of the management (Lei et al., 2020), and then enhance the creation of enterprise value. Based on the opportunistic hypothesis, some scholars pointed out that on the one hand, D&O insurance diverts the responsibility and risk of management, stimulates its opportunistic motivation to seek personal interests, and hurts corporate governance (Boyer and Stern, 2013). On the other hand, D&O insurance provides a bottom line for management's investment and decision-making behavior, which may reduce the deterrent effect of legal proceedings, and may even further exacerbate principal-agent conflicts (Gillan and Panasian, 2015).

2.2 Economic consequences of D&O insurance

Since the corporate governance effects of D&O insurance are divergent, to further investigate which hypothesis dominates, scholars further investigate the economic consequences of D&O insurance from the perspectives of business risk, corporate value, innovation-decision, and investment financing concerning the characteristics of their respective capital markets.

In terms of operational risk, scholars have found that D&O insurance has a strong risk transfer function, which helps to alleviate the contradiction of risk aversion of managers and enhance the risk-bearing capacity of enterprises (Hu and Hu, 2017; Wen, 2017). In terms of corporate value, scholars believe that D&O insurance can help improve its profitability and market value. Zou et al. (2008) found that there is a critical value between D&O insurance and enterprise value, showing an inverted U-shaped relationship. Jia et al. (2019) found that D&O insurance can enhance firm value by reducing inefficient investments and that the nature of state ownership and increased equity concentration reduce this enhancement. In terms of enterprise innovation decision-making, D&O insurance can help improve the risk tolerance of managers, thereby promoting the level of independent innovation of enterprises. Fang and Qin (2018) empirically found that the subscription of

D&O insurance by enterprises is conducive to reducing the level of concern about management decision-making risks, and positively improves enterprise innovation decision-making, and the incentive effect is less in high-tech industries, state-owned property rights, and management's shareholding more significant in companies. Li and Xu (2020) found that D&O insurance can help improve the level of risk-taking and management efficiency and then significantly improve the innovation output and innovation efficiency of enterprises. In terms of investment and financing, Hu and Hu (2017) took Chinese listed companies as the research object and found that D&O insurance is selective in the impact of inefficient investment, over-investment behavior can be supervised, while under-investment has not been significantly Effect. From the perspective of external financing, Lin et al. (2011) discussed whether D&O insurance induces opportunistic investment by management. They found that the higher the D&O insurance premium, the more frequent but less efficient the external financing of the firm. Li (2020) found that insurance-purchasing firms were subject to stricter financing constraints compared to firms that did not purchase D&O insurance and that the positive relationship was more pronounced among firms with non-state ownership, dual employment, and lower regional marketization.

In summary, there is no unified academic conclusion on the supervisory governance effect or opportunistic effect of D&O insurance. The reasons for the discrepancy may be the following. First, the research samples are different. In developed countries, the D&O insurance started early, the coverage rate is high, and the system is more well developed. In contrast, China's D&O insurance started late and has a low coverage rate. Therefore, differences in sample selection and period, etc., may have an impact on the results. Second, the metrics of D&O insurance are different. The China Securities Regulatory Commission (CSRC) has not yet mandated companies to disclose the premium amount of D&O insurance. Therefore, most Chinese scholars have studied whether firms purchase D&O insurance as a dummy variable. In contrast, the development of foreign mechanisms in the D&O insurance system has been more mature, scholars will also include the amount of D&O insurance premiums, and insurance ratios into the analysis, the research perspective is more diverse. Third, when analyzing the economic consequences of D&O insurance based on different research perspectives, scholars have chosen different moderating and mediating variables, which may also make a difference to the research results.

2.3 Factors influencing ESG performance

The growing focus on environmental changes, social events, and corporate responsibility has triggered a trend that a substantial body of literature developed to monitor ESG performance. By combing through the extant literature, we found most previous research on the factors influencing ESG performance has been based on the perspective of market

characteristics, firm leadership characteristics, and ownership characteristics. As for market characteristics, many studies have provided evidence that a country's economic development (Cai et al., 2016), industry (Borghesi et al., 2014), political leanings of the state's citizens (Liang and Renneboog, 2013), the social capital of the county (Jha and Cox, 2015) affect ESG performance. Firm leadership characteristics include multinational board members (Iliev and Roth, 2020), women leaders (McGuinness et al., 2017), married CEOs (Hegde and Mishra, 2017), CEO confidence (McCarthy et al., 2017), and CEO pay (Ikram et al., 2019). Other studies argue that firms' ESG performance is associated with the size of institutional ownership (Chen et al., 2016), family ownership (El Ghoul et al., 2016), and state ownership (Boubakri et al., 2016).

However, whether D&O insurance can effectively play a role in corporate governance to improve corporate ESG performance remains to be studied. According to existing theories, on the one hand, the supervisory and governance role of D&O insurance can urge companies to improve the quality of ESG information disclosure and facilitate stakeholders' monitoring of corporate ESG performance. In addition, it can also motivate management to be diligent, focus on long-term development goals, improve risk-taking ability, and actively participate in green innovation activities, which can ultimately improve ESG performance. On the other hand, the "bottom line" effect of D&O insurance may also stimulate moral hazard and opportunistic behavior of directors and executives, causing managers to act to satisfy their interests at the expense of corporate sustainability, leading to a decline in corporate ESG performance. Therefore, the actual effect of D&O insurance on ESG performance is an important issue for empirical research.

3 Theoretical analysis and hypothesis developments

3.1 D&O insurance and ESG performance

ESG performance differs from traditional financial indicators in that it comprehensively considers whether an enterprise can achieve long-term sustainable development from three dimensions: environment, society, and corporate governance. Among them, E mainly emphasizes that enterprises take the initiative to protect the environment, adopt environmental protection measures and incorporate environmental protection into the company's constitution; S requires enterprises to comply with social morality, rule of law, and ethics, assume and protect the rights and interests of various stakeholders; G represents the corporate governance system established by the company to maintain orderly operation.

In the past 2 decades, with the evolvement of sustainability reporting and integrated reporting, an increasing number of entities started to realize the importance of ESG (Camilleri, 2015). Firstly, they may be influenced by regulatory pressures

and stakeholders' expectations (Brammer et al., 2011; Golob et al., 2013). According to the stakeholder theory and legitimacy theory, companies attempt to disclose ESG performance to maintain and repair their legitimacy among stakeholders, which further helps them satisfy stakeholders' expectations and forge strong relationships with stakeholders (De Villiers et al., 2017; Camilleri, 2018). Secondly, ESG disclosures become widely accepted across companies and are closely related to the companies' institutional context (Adams et al., 2016; Nirino et al., 2021). On one hand, companies disclose ESG to improve their reputation and offset the threat of regulation. On the other hand, irresponsible companies will be severely punished by socio-political forces and pressure groups if they do not respect societal norms and ethical values (Elving et al., 2015; Camilleri, 2018). Thirdly, following the resource-based view (RBV), environmental and social activities can lead to the development of a competitive advantage within a company (Hull and Rothenberg, 2008; Camilleri, 2015; 2018). Hence, companies have an incentive to improve their ESG performance to access resources that affect the survival and development of the company.

Previous studies have suggested that D&O insurance can provide a "bottom line" effect for the management in terms of behavior and personal property (Wang et al., 2020). However, this "bottom line" effect may have positive or negative effects on the management of the company. Therefore, D&O insurance may also have positive or negative effects on corporate ESG performance.

In terms of positive impact, D&O insurance can encourage managers to make positive progress, forcing managers to engage in responsible conduct and improve corporate ESG performance. On one hand, D&O insurance can lower directors' and officers' litigation exposures, alleviate the potential risk aversion problem and increase their risk appetite, thereby stimulating them to invest more in innovation (Hu et al., 2019). Moreover, before a company subscribes to D&O insurance, the insurance company often requires the client company to appoint enough independent directors to reduce the risk (O'Sullivan 2002). The independent directors are more inclined to focus on business development and governance efficiency (Wang and Lu 2013) to prove they are diligent and responsible. Meanwhile, the independence of independent directors enables them to make independent judgments on the company's decision-making and development strategies objectively and neutrally and to focus on long-term development rather than current interests (Wang and Chen 2018). Hence, independent directors are more likely to support green technology innovation, which has been increasingly emphasized by policymakers and academics alike as a mechanism for effectively solving environmental problems and enhancing firm sustainability (Kallio and Nordberg 2016).

On the other hand, after an enterprise subscribes to D&O insurance, the insurance company will participate in corporate

governance as a third-party external supervisor, which can reduce the information asymmetry and investment concerns of external stakeholders, thus helping to improve the availability of exogenous financing. According to the “signaling” hypothesis, the fulfillment of environmental and social responsibilities will lead stakeholders to believe that the company’s performance is good enough to support its continued sustainability practices. Hence, companies tend to undertake social responsibilities to form reputation capital, which can also help the company better survive the legitimacy crisis especially when the company is affected by negative events (Dowling and Pfeffer 1975; Broadstock et al., 2021).

In contrast, the negative impact of D&O insurance is manifested in its “bottom line” effect that can induce unintended moral hazards, gradually becoming a “protective umbrella” for management’s self-interested behavior (Chung and Wynn, 2014). On one hand, the introduction of D&O insurance may reduce the diligence of management in performing their duties (Gillan and Panasian 2015; Jia and Tang 2018), leading to managerial opportunism. On the other hand, D&O insurance reduces the disciplining effect of shareholder litigation, which may lead to the waste or improper use of corporate resources and shareholders’ interests. In turn, it may hurt business management and cause firms to reduce long-term corporate value enhancement activities, which finally hurts corporate ESG performance.

Therefore, we propose two competing hypotheses for the effect of D&O insurance on corporate ESG performance.

H1a: The purchase of D&O insurance improves corporate ESG performance, other things being equal.

H1b: The purchase of D&O insurance decreases corporate ESG performance, other things being equal.

3.2 The moderating effect of economic policy uncertainty

According to the real options theory, firms exercise increasingly prudent investment behavior and tend to reduce or postpone long-term ESG investment in response to the high uncertainty of economic policies (Bloom et al., 2016). This is because improving ESG performance requires a large amount of sunk costs, while companies prefer to hold more cash or increase dividend payout during a high EPU period. At the same time, the incentive and supervisory functions of D&O insurance are largely dependent on the external environment of the company (Jia and Liang 2013; Feng et al., 2017). On one hand, the external environment may affect people psychologically and change their expectations. The theory of attribution suggests that people tend to underestimate the impact of external factors and overestimate the impact of internal or personal factors. Thus, directors and officers are more likely to be blamed for the enterprise’s distress, which rises

the legitimacy risk faced by management (Lou et al., 2022). Thus, the “bottom line” effect provided by D&O insurance is diminished when EPU grows. On the other hand, EPU may reduce the observability of management’s diligence and create information asymmetries between management and the stakeholders (Boyle and Guthrie 2003), encouraging directors and officers to adopt opportunistic practices (Johnson et al., 2000; Bae et al., 2012) rather than improving corporate ESG performance. Following the empirical evidence and the above discussion, we propose the following hypothesis:

H2: Economic policy uncertainty negatively moderates the relationship between D&O insurance and corporate ESG performance.

3.3 The moderating effect of industry competition

According to strategic management theory and signaling theory, companies need to pay attention to the dynamic requirements of various stakeholders to gain a sustainable competitive advantage. The intensified competition will inevitably lead to a large number of substitutes in the market. At this time, consumers tend to choose goods produced by companies with a good reputation and excellent ESG performance (Brammer and Pavelin, 2004). Therefore, companies have the incentive to practice environmental, social, and corporate governance responsibilities to release positive signals about their operations and development to the outside. In addition, the competitive information hypothesis suggests that when the industry becomes more competitive, it provides a more transparent information environment for the management. Therefore, independent directors can perform advisory and monitoring functions at lower monitoring costs. Meanwhile, it also makes management under greater pressure for performance evaluation and is faced with a higher risk of business failure and departure. At this time, the signaling effect of the company’s subscription to D&O insurance is reduced, and the effect on ESG performance is diminished. Based on this, this paper proposes the following hypothesis:

H3: Industry competition negatively moderates the relationship between D&O insurance and corporate ESG performance.

4 Research design

4.1 Sample selection and data source

To ensure consistency and availability of research data, we based our sample selection on all firms listed on the Shanghai and Shenzhen Stock Exchanges from 2011 to 2020. At present, the China Securities

Regulatory Commission (CSRC) follows the principle of voluntary disclosure to disclose information related to D&O insurance. For this reason, we manually compile information about D&O insurance (*Insured*) by reviewing the annual reports of listed companies and combining them with the announcements of listed companies downloaded from China Information Bank. ESG disclosure scores (*ESG*) are obtained from Bloomberg, economic policy uncertainty (*Epu*) constructed from the China Economic Policy Uncertainty Index. The rest of the data are obtained from the China Stock Market and Accounting Research (CSMAR) Database. To improve the reliability and validity of the data, the initial sample is excluded as follows: 1) Financial and insurance industry; 2) ST and *ST companies; 3) Companies with missing relevant financial data. After the above processing, we finally obtained a sample of 6,223 firm-years observations. To avoid the impact of extreme values on the accuracy of the empirical results, all continuous variables are Winsorized at the upper and lower 1% levels. The statistical analysis software is Stata 16.0.

4.2 Variable definition

4.2.1 Explained variable (ESG)

Bloomberg measures ESG performance in terms of environment (E), society (S), and governance (G) dimensions. The scale ranges from 0.1 to 100, meaning that the more data disclosed, the higher the level of disclosure, and the better the ESG performance. In addition, the Bloomberg database is weighted based on the importance of the data points and adjusted accordingly for each industry.

4.2.2 Main explanatory variable (Insured)

Overseas research on D&O insurance mostly uses the amount of D&O insurance as a proxy variable. Chinese companies are not mandated to disclose the specific amount of D&O insurance. Therefore, we draw on the studies of Lin et al. (2011) and Yuan et al. (2016) to select a binary dummy variable *Insured* to measure the purchase of D&O insurance. A listed company is considered to have purchased D&O insurance if the information related to the purchase of D&O insurance is disclosed in its announcement and voted by the board of directors and shareholders' meeting, *Insured* = 1; conversely, *Insured* = 0.

4.2.3 Moderating variables

Our study draws on the Chinese economic policy uncertainty index developed and compiled by Baker et al. (2013) to measure economic policy uncertainty. However, the economic policy uncertainty data given by Baker et al. (2013) are monthly data. Following Zhang and Wang (2021), the annual data on economic policy uncertainty is obtained by arithmetically averaging the monthly data for each year and dividing it by 100.

Referring to scholars such as Peress (2010) and Sun et al. (2021), the industry Lerner index is used to measure the degree of

industry competition. The industry Lerner index is obtained by using the ratio of the operating revenue of individual companies to the operating revenue of a single industry and then weighting the individual Lerner index within the industry.

$$\text{Individual Lerner Index} = (\text{Operating Revenue} - \text{Operating Costs} - \text{Selling Expenses} - \text{Administrative Expenses}) / \text{Operating Revenue}$$

It should be noted that the higher the industry Lerner Index is, the stronger the monopoly power in the industry and the less competitive the industry is.

4.2.4 Control variables

Our firm-specific control variables are defined in previous studies such as Arora and Dharwadkar (2011) and Zamir et al. (2020), to capture the effect of other factors on ESG performance. The detailed definitions of all variables used in this study are presented in Table A1.

4.3 Model design

Model Eq. 1 is used to test hypothesis H1, which examines the effect of D&O insurance on corporate ESG performance. Our study uses the firm-fixed effects model to control for unobserved time-invariant firm characteristics. We also use the heteroscedasticity-robust standard errors clustered by firms for statistical inference.

$$ESG_{it} = \alpha_0 + \alpha_1 Insured_{it} + \alpha_2 Controls_{it} + \sum Firm + \sum Year + \varepsilon_{it} \quad (1)$$

To test how economic policy uncertainty and industry competition influence the relationship between D&O insurance and corporate ESG performance, the baseline regression Eq. 1 is augmented as follows:

$$ESG_{it} = \beta_0 + \beta_1 Insured_{it} + \beta_2 Epu_{it} + \beta_3 Insured_{it} * Epu_{it} + \beta_4 Controls_{it} + \sum Firm + \sum Year + \varepsilon_{it} \quad (2)$$

$$ESG_{it} = \gamma_0 + \gamma_1 Insured_{it} + \gamma_2 Gglerner_{it} + \gamma_3 Insured_{it} * Gglerner_{it} + \gamma_4 Controls_{it} + \sum Firm + \sum Year + \varepsilon_{it} \quad (3)$$

5 Empirical results

5.1 Descriptive statistics

Table 1 shows the descriptive statistics results of the main variables. The mean value of ESG performance (*ESG*) is

TABLE 1 Descriptive statistics.

Variables	Obs.	Mean	SD	Min	Max
ESG	6,223	22.430	6.341	11.980	44.810
Insured	6,223	0.137	0.344	0.000	1.000
Lev	6,223	0.471	0.187	0.075	0.844
CFO	6,223	0.062	0.062	−0.101	0.241
Size	6,223	23.24	1.307	20.580	27.030
Incentives	6,223	14.75	0.680	13.300	16.720
Mgtexpense	6,223	0.074	0.052	0.007	0.273
Audit4	6,223	0.133	0.340	0.000	1.000
State	6,223	0.596	0.491	0.000	1.000
Dual	6,223	0.163	0.369	0.000	1.000

22.43 and the standard deviation is 6.341, indicating that there are significant differences in ESG performance among different companies. The mean value of D&O insurance (*Insured*) is 0.137, which shows that only 13.7% of the enterprises in the study sample have purchased D&O insurance, reflecting that the percentage of enterprises purchasing D&O insurance among A-share listed companies in China is still low and there is a significant gap with Western countries.

5.2 Baseline regression results

Table 2 presents the regression results for the test of H1. As shown in columns (1) and (2) of Table 2, regardless of whether control variables were included or not, D&O insurance coefficients ($\alpha_1 = 5.491$ and 2.921, respectively) were significantly positive at the 1% level, indicating that D&O insurance can significantly enhance corporate ESG performance. The regression results reported in columns (2) of Table 2 further confirm H1a.

5.3 Regression results for moderating effects

Table 3 presents the regression results for the test of the moderating effect of Economic Policy Uncertainty and Industry competition. Columns (1) to (2) are respectively based on the regression results of models Eqs 2, 3. Table 3 shows that when economic policy uncertainty (*Epu*) increases, the contribution of D&O insurance to corporate ESG performance is weakened, which suggests that the interaction effect of economic policy uncertainty and D&O insurance have a substitution effect on corporate ESG performance. In addition, based on the new institutional economics, it has been argued that competition can generate financial pressure on firms and management,

TABLE 2 The impact of D&O insurance on ESG performance.

ESG	(1)	(2)
Insured	5.491*** (18.811)	2.921*** (11.129)
Lev		−1.224*** (−2.609)
CFO		2.759** (2.501)
Size		1.569*** (19.400)
Incentives		0.457*** (3.744)
Mgtexpense		2.770* (1.950)
Audit4		3.169*** (10.986)
State		0.723*** (4.836)
Dual		−0.327* (−1.773)
Constant	17.690*** (50.760)	−22.939*** (−11.061)
Obs.	6,223	6,223
Adj.R ²	0.161	0.316
Year	Yes	Yes
Industry	Yes	Yes

Notes: ***, **, and * indicate significant difference at the 1%, 5%, and 10% levels, respectively. T-statistics are reported in parentheses and are based on robust standard errors.

thus forming an alternative governance mechanism (Aghion et al., 1999). Therefore, a more competitive market environment is less conducive to the role of fault-tolerant incentives. Column (2) of Table 3 shows that the higher the industry competition, the less effect introducing D&O insurance on ESG performance.

6 Robustness tests

6.1 Dealing with endogeneity

It is possible that the purchase of D&O insurance is endogenous, which is to say, both D&O insurance and corporate ESG performance are jointly determined by unobservable factors. In this section, we aim to address this type of endogeneity issue using the following approaches.

First, to mitigate the possible self-selection problem of the purchase of D&O insurance that affects the accuracy of the research results, this paper adopts Heckman's two-stage regression. In the first stage, we consider the influence of

TABLE 3 Test for moderating effects.

ESG	(1)	(2)
Insured	2.908*** (11.141)	2.921*** (11.072)
EPU	−7.680*** (−3.859)	
EPU * Insured	−8.408*** (−4.406)	
Gglerner		−3.563*** (−5.304)
Gglerner * Insured		4.175* (1.954)
CVs		
Constant	−10.214** (−2.530)	−23.998*** (−11.584)
Obs.	6,223	6,223
Adj.R ²	0.319	0.321
Year	Yes	Yes
Industry	Yes	Yes

Notes: ***, **, and * indicate significant difference at the 1%, 5%, and 10% levels, respectively. T-statistics are reported in parentheses and are based on robust standard errors.

factors such as financial status and corporate governance characteristics on the demand for D&O insurance, and build a Probit model to estimate the inverse Mills ratio (*IMR*) of directors' liability insurance for listed companies; In the second stage, we add the inverse Mills ratio (*IMR*) of D&O insurance for listed companies estimated in the first stage to model Eq. 1. Columns (1) of Table 4 suggest that our conclusion is still robust.

Second, we applied the instrumental variable (IV) estimation method. Drawing on Yuan et al. (2016) and Gao et al. (2021), we use the overseas work background of executives (*Abroad*) as an instrumental variable for D&O insurance to carry out 2SLS regression. The instrument variable is measured by taking the logarithm of the number of corporate executives with overseas working backgrounds. On one hand, the coverage rate of D&O insurance in developed countries such as Europe and the United States has reached over 90%, thus executives with overseas working backgrounds have a better understanding of the mechanism of the role of directors' liability insurance. According to the “branding theory” and “cognitive consistency theory,” the values and preferences of executives with overseas working backgrounds are influenced by western companies, and they tend to purchase D&O insurance after returning to work in China. Therefore, we expect that the higher the number of executives with overseas working backgrounds, the more likely the company is to purchase D&O insurance, which satisfies the correlation condition of an instrumental variable. On the other hand, the executive's

TABLE 4 Endogenous test.

	(1)	(2)	(3)
	ESG	Insured	ESG
Insured	2.920*** (11.126)		12.00** (2.83)
Abroad		0.045*** (4.52)	
IMR	0.056 (0.131)		
CVs	Yes	Yes	Yes
F	63.33	14.92	171.6
Obs.	6,223	6,223	6,223
Year	Yes	Yes	Yes
Industry	Yes	Yes	Yes
Kleibergen-Paap rk LM statistic			14.779
Cragg-Donald Wald F statistic			20.399 [16.38]

Notes: ***, **, and * indicate significant difference at the 1%, 5%, and 10% levels, respectively. T-statistics are reported in parentheses and are based on robust standard errors. Values in square brackets are critical values at the 10% level of the Stock-Yogo test.

overseas work background can hardly have a direct impact on the corporate ESG performance, satisfying the exogenous condition of the instrumental variable. The regression results in columns (2) and (3) of Table 4 show that the regression coefficient of D&O insurance (*Insured*) continues to positively contribute to corporate ESG performance at the 5% significance level. Meanwhile, the F-value of the first stage regression of the instrumental variables is greater than 10, and the Wald F statistic in the second stage regression is greater than the Stock-Yogo critical value of 16.38 at the 10% level, which rejects the hypothesis of weak instrumental variables and indicates that the selected instrumental variables are valid.

6.2 Other robustness tests

First, the estimation error caused by omitted variables is further solved to a certain extent by controlling for individual effects and year effects in the baseline model.

Second, to exclude the possible existence of endogeneity problems such as reverse causality, we lag the explanatory variable (*Insured*) in model Eq. 1 by one period. As shown in columns (2) of Table 5, which suggests that our conclusion is still robust.

Third, to more accurately compare the impact of the introduction of D&O insurance on ESG performance, we exclude the industries that never introduced D&O insurance in recent years. The regression results are reported in column (3) of Table 5, we find that our results hold after excluding these samples.

Fourth, since the introduction of D&O insurance by Chinese listed firms is still low, there may be a screening phenomenon of

insured firms by insurance companies, i.e., only firms with inherently excellent financial and ESG performance can purchase D&O insurance. For this reason, we performed a propensity score-matched (PSM) estimation. To begin with, the Probit model is set up, with D&O Insurance (*Insured*) as the dependent variable. The independent variables include *Balance Sheet Ratio*, *Cash Ratio*, *Corporate Size*, *Executive Incentive*, *Management Expense Ratio*, *Corporate Age*, *Top Ten Shareholders' shareholding*, *Profitability*, and *Corporate Growth*. The comparison of differences before and after matching variables is presented in Table A2. The estimation applies a one-to-one paring principle to the matching sample. Based on the new paired sample, column (4) of Table 5 shows similar results to our main regression, which supports that our results are not driven by self-selection.

7 Additional analyses

7.1 Mediating effect analysis

In the previous section, we provide evidence that D&O insurance plays an important role in improving corporate ESG performance, but the transmission mechanism between the two remains at the theoretical level. In this section, we construct models Eqs 4–6 to empirically test two possible mediating paths: improving independent director function-performing effectiveness (*Scores*) and increasing corporate risk-taking (*Risk*).

$$ESG_{it} = \alpha_0 + \alpha_1 Insured_{it} + \alpha_2 Controls_{it} + \sum Firm + \sum Year + \varepsilon_{it} \quad (4)$$

$$Scores_{it} / Risk_{it} = \delta_0 + \delta_1 Insured_{it} + \delta_2 Controls_{it} + \sum Firm + \sum Year + \varepsilon_{it} \quad (5)$$

$$ESG_{it} = \mu_0 + \mu_1 Insured_{it} + \mu_2 Scores_{it} / Risk_{it} + \mu_3 Controls_{it} + \sum Firm + \sum Year + \varepsilon_{it} \quad (6)$$

Following Jia and Tang (2018), this study selects four indicators: the busyness of independent directors, the level of independent directors' remuneration, the number of meetings attended by independent directors, and the proportion of independent directors, using the entropy method to calculate the comprehensive score of independent directors' performance, the specific indicators are shown in Table 6. In addition, we also use the comprehensive score of independent directors' performance calculated by the CRITIC assignment method as a robustness test.

The regression results are presented in Table 7, D&O insurance improves the effectiveness of independent directors in performing their duties. When a company

TABLE 5 Other robustness tests.

ESG	(1)	(2)	(3)	(4)
Insured	2.352*** (5.830)		2.906*** (11.086)	2.321*** (7.078)
L.Insured		3.118*** (10.569)		
Lev	−1.312** (−2.214)	−1.022** (−2.009)	−1.239*** (−2.596)	1.276 (1.137)
CFO	1.206 (1.334)	3.358*** (2.725)	2.818** (2.493)	4.134 (1.512)
Size	1.036*** (5.556)	1.613*** (18.597)	1.583*** (19.336)	2.165*** (13.389)
Incentives	0.561*** (3.578)	0.532*** (4.028)	0.482*** (3.875)	0.833*** (3.295)
Mgtexpense	4.338** (2.562)	2.329 (1.517)	3.024** (2.078)	20.607*** (4.762)
Audit4	1.162** (2.039)	3.348*** (10.733)	3.144*** (10.896)	3.766*** (8.385)
State	0.311 (1.029)	0.761*** (4.721)	0.752*** (4.985)	0.876** (2.262)
Dual	−0.056 (−0.295)	−0.262 (−1.303)	−0.299 (−1.592)	−0.795 (−1.421)
Constant	−14.136*** (−3.172)	−25.769*** (−11.498)	−21.703*** (−9.952)	−45.863*** (−10.107)
Obs.	6,223	5,492	6,094	1708
Adj.R ²	0.774	0.325	0.313	0.426
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
Firm	Yes	No	No	No

Notes: ***, **, and * indicate significant difference at the 1%, 5%, and 10% levels, respectively. T-statistics are reported in parentheses and are based on robust standard errors.

purchases D&O insurance, the independent directors will actively promote the effectiveness of their performance to prove they are diligent and responsible. Further, the extensive experience and social resources of independent directors can also send positive signals and alleviate information asymmetry, thus significantly improving the ESG performance of the company.

Referring to scholars such as John et al. (2008) and He et al. (2019), we use the volatility of a firm's earnings to measure corporate risk-taking. First, as shown in model Eq. 7, we subtract the industry average from the company's annual Roa to mitigate the effects of industry and cycles. Second, as shown in models Eqs 8, 9, we take every 5 years ($t - 2$ to $t + 2$) as an observation period and calculate the standard deviation and extreme deviation of industry-adjusted Roa (Adj_Roa_{it}). Finally, to make the results more intuitive, we multiply the above results by 100 to obtain *Risk1* and *Risk2* as proxies for the level of enterprise risk-taking.

TABLE 6 Effectiveness of independent directors' performance.

Variable	Definition	Measurement
Busy	The busyness of independent directors	The average number of companies concurrently held by independent directors
Payments	Independent directors' remuneration	Natural logarithm of the average remuneration of independent directors
Meetings	Number of meetings attended by independent directors	Number of attendance - number of delegated attendance - number of absences
Ind_ratio	The proportion of independent directors	Number of independent directors/number of directors

TABLE 7 Intermediary mechanism tests (1).

	(1)	(2)	(3)	(4)	(5)
	ESG	Score1	ESG	Score2	ESG
Insured	2.966*** (11.168)	0.009*** (5.295)	2.924*** (11.004)	0.258*** (6.459)	2.880*** (10.867)
Score1			4.816*** (2.627)		
Score2				0.336*** (4.488)	
CVs	Yes	Yes	Yes	Yes	Yes
Constant	−22.915*** (−11.037)	0.057*** (4.109)	−23.191*** (−11.121)	0.008 (0.020)	−22.918*** (−11.097)
Obs.	6,213	6,213	6,213	6,213	6,213
Adj.R ²	0.317	0.068	0.317	0.168	0.319
Year	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes	Yes

Notes: ***, **, and * indicate significant difference at the 1%, 5%, and 10% levels, respectively. T-statistics are reported in parentheses and are based on robust standard errors.

TABLE 8 Intermediary mechanism tests (2).

	(1)	(2)	(3)	(4)	(5)
	ESG	Risk1	ESG	Risk2	ESG
Insured	2.418*** (8.343)	0.006** (2.464)	2.433*** (8.384)	0.013** (2.332)	2.433*** (8.385)
Risk1			−2.602** (−2.163)		
Risk2					−1.157** (−2.293)
CVs	Yes	Yes	Yes	Yes	Yes
Constant	−16.326*** (−7.307)	0.093*** (3.678)	−16.085*** (−7.210)	0.240*** (3.962)	−16.049*** (−7.193)
Obs.	4,751	4,751	4,751	4,751	4,751
Adj.R ²	0.286	0.117	0.287	0.120	0.287
Year	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes	Yes

Notes: ***, **, and * indicate significant difference at the 1%, 5%, and 10% levels, respectively. T-statistics are reported in parentheses and are based on robust standard errors.

$$Adj\_Roa_{it} = \frac{EBIT_{it}}{ASSET_{it}} - \frac{1}{X} \sum_{k=1}^X \frac{EBIT_{it}}{ASSET_{it}} \quad (7)$$

$$Risk_{it} = \sqrt{\frac{1}{T-1} \sum_{t=1}^T \left(Adj\_Roa_{it} - \frac{1}{T} \sum_{t=1}^T Adj\_Roa_{it} \right)^2} \quad T=5 \quad (8)$$

$$Risk2_{it} = Max(Adj\_Roa_{it}) - Min(Adj\_Roa_{it}) \quad (9)$$

Columns (2) and (4) of Table 8 indicate that D&O insurance increases enterprise risk-taking. Further, after adding the Risk1/Risk2 to model Eq. 4, the coefficient of *Insured* is increased from 2.418, when there is no mediating variable, to 2.433. It indicates that D&O insurance can lower directors' and officers' litigation exposures, and increase enterprise risk-taking. Meanwhile, the underwriting effect of D&O insurance can transfer the financial losses caused by the top management's decision errors to the insurance company, thus greatly eliminating the managers' concerns and motivating them to choose green innovation activities that are beneficial to improving corporate ESG performance.

8 Conclusion and future research directions

8.1 Conclusion

D&O insurance was introduced to the Chinese capital market in 2002, but after 2 decades of development, the current insurance coverage rate for Chinese A-share listed companies is less than 15%. In Europe and the United States and other developed capital markets, the insured rate of D&O insurance is mostly above 90%. Thus, it can be seen that D&O insurance is still in the initial stage of development in the Chinese capital market, and there is still much room for future development, and the governance effect of D&O insurance in the Chinese capital market needs to be further examined. At the same time, promoting the construction of an ecological civilization system is an important part of achieving high-quality economic development in China. As enterprises are responsible for environmental pollution and resource consumption, it is worthwhile to study how to better guide and motivate them to improve their ESG performance and achieve a win-win situation

between environmental management and economic development. Therefore, this study attempts to examine the impact of corporate on ESG performance from the perspective of D&O insurance, a governance mechanism, and insurance instrument. We find that D&O insurance can improve corporate ESG performance and when economic policy uncertainty and industry competition rise, the contribution of D&O insurance to ESG performance weakens. Additional analysis suggests that this promotion is achieved by improving independent director function-performing effectiveness and increasing corporate risk-taking.

This paper argues that the above research findings have important theoretical value and policy implications. At the theoretical level, this paper examines the role of D&O insurance on corporate ESG performance and the specific impact mechanisms from a corporate governance perspective. It provides new evidence for the management incentive hypothesis and the external monitoring hypothesis of D&O insurance and further complements the research on the economic consequences and governance effects of D&O, which is also an important reference for an in-depth understanding of the governance effects of D&O insurance in emerging capital markets. Specifically, our research enriches the extant literature by taking the D&O insurance as an example to uncover a new factor affecting corporate ESG performance within a broader legitimization strategy. Further, our study analyzes the comprehensive governance consequences of D&O insurance from the perspective of ESG. Third, our study revealed the transmission mechanisms of D&O insurance to ESG. It deepens the understanding of the relationship between D&O insurance and corporate ESG performance.

The practical enlightenment offered by our study lies in the following. First, D&O insurance is an external corporate governance mechanism that can have a positive governance effect and help companies improve their ESG performance. Therefore, for the Chinese capital market, which is in a special period of emerging and transition, the legislature and regulatory authorities should guide and encourage listed companies to introduce D&O insurance governance mechanisms promptly according to their corporate governance level, risk profile, and other factors. Second, the study finds that D&O insurance can improve corporate ESG performance by enhancing management risk-taking and improving independent director function-performing effectiveness. Therefore, when companies introduce the governance mechanism of D&O insurance, they should understand the functions of D&O insurance comprehensively and correctly. To improve the incentive and restraint mechanism for the main body of officers and directors, the synergistic effect of the two can be brought into play, so that the management can better fulfill its fiduciary duties and ultimately improve the ESG performance of the enterprise. Third, insurance institutions should optimize the contract design of D&O insurance. At present, China's D&O insurance has some overly restrictive clauses and vague judgment criteria. The development of D&O insurance in China's capital

market is relatively late, so some foreign standards are inevitably used in the process of implementation. However, there are differences in the national conditions of each country, and to further promote the development of D&O insurance in the Chinese capital market, it is necessary to set up insurance clauses by the national conditions of China.

8.2 Limitations and further research

Constrained by the availability of data and the level of research, there are some limitations in this paper. The China Securities Regulatory Commission (CSRC) has not yet made it mandatory for companies to disclose information related to D&O insurance subscriptions, and therefore detailed data on D&O insurance premiums and insurance amounts are not fully available. Therefore, we can only examine the economic impact of D&O insurance in the form of dummy variables, which can be improved in subsequent studies as corporate information disclosure becomes more transparent and specific. In addition, the governance functions, pathways, and interactions with other mechanisms of D&O insurance can be further studied to maximize its positive governance functions.

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

Conceptualization: JZ and HX. Methodology: JZ. Writing-original draft preparation: JZ. Writing-review and editing: JZ and HX. All authors have read and approved the final manuscript.

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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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Appendix

TABLE A1 Definition of variables.

Variable	Measurement
ESG	Bloomberg database ESG performance
Insured	Dummy variable. Takes the value of 1 if the company purchased director's liability insurance during the year, and 0 otherwise.
Lev	Total liabilities/total assets
Mgtexpense	Total administrative expenses/total assets
CFO	Net cash flow from operating activities/total assets
Size	Natural logarithm of total assets
Incentives	Natural logarithm of the annual salary of the top three executives in terms of annual salary amount
Dual	Dummy variable. If the general manager and the chairman are the same people, the value is 1, otherwise, it is 0.
Audit4	Dummy variable. Its value is 1 if it is audited by the Big 4 and 0 otherwise.
State	Dummy variables. State-owned enterprises take 1, otherwise, take 0.
Firm	Individual dummy variables
Year	Year dummy variables

TABLE A2 Comparison of differences before and after matching variables.

Variable	U (Before matching)	Average value		Deviation	Degree of reduction of deviation	T-test	
	M (After matching)	Processing group	Control group			T value	P value
Lev	U	0.536	0.46	42.5		11.18	0.000
	M	0.536	0.537	−0.3	98.8	−0.07	0.946
CFO	U	0.065	0.615	5.7		1.48	0.140
	M	0.065	0.066	−2.3	59.5	−0.49	0.627
Size	U	24.149	23.092	3.7		22.85	0.000
	M	24.149	24.087	−6.6	94.1	0.91	0.365
Incentives	U	15.068	14.699	53.6		14.99	0.000
	M	15.068	15.063	0.7	98.7	0.14	0.889
Mgtexpense	U	0.057	0.763	−42.3		−10.47	0.000
	M	0.057	0.056	−0.2	99.6	−0.04	0.972
Age	U	15.782	13.636	35.9		9.67	0.000
	M	15.782	15.735	0.8	97.8	0.16	0.871
Big10	U	65.299	57.264	48.8		13.92	0.000
	M	65.299	64.721	3.5	92.8	0.74	0.461
ROA	U	0.04	0.507	−18.7		−4.61	0.000
	M	0.04	0.041	−0.5	97.6	−0.09	0.925
Growth	U	0.113	0.181	−6.2		−1.30	0.192
	M	0.113	0.114	−0.1	98.9	−0.04	0.965



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Does climate change affect enterprises' ability to sell their products?

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Based on local cities' climate change data and the operating income data of Chinese listed enterprises from 2008 to 2019, we study the impact of climate change on enterprises' sales ability and analyze its subsequent influence on their sales revenue from three dimensions: inside enterprises, the supply side and the demand side. The results show that climate change reduces enterprises' sales revenue. From enterprises' internal perspective, climate change reduces production efficiency, increases management costs and the impact on the cost of sales is not obvious. From the demand side, climate change increases business risks and reduces transactions between large customers and enterprises. The share of sales from large customers is reduced, but no obvious impact is observed for small customers. On the supply side, climate change reduces business credit levels, which in turn reduces sales revenue. A heterogeneity analysis shows that the impact of climate change on sales revenue is more obvious in private enterprises, enterprises with weak internal controls and enterprises in central and western regions of China.

KEYWORDS

climate change, rising temperatures, sales power, company ability, product selling

Introduction

Two important problems are currently affecting our climate. First, the global average temperature is increasing annually. Second, extreme weather is becoming increasingly common and the frequency of heat waves in some regions has more than doubled and is expected to increase nearly five times in the next 50 years (Lau and Nath, 2012). Thus, climate change is one of the important challenges facing the world today with a significant socio-economic impact on peoples' lives (Pankratz et al., 2019). Humans live in a warming natural environment; hence, global warming is the most prominent feature of climate change. Increasingly severe global warming and related patterns seriously threaten human development. In 2018, the United Nations Intergovernmental Panel on

Climate Change (IPCC) released the *Special Report on Global Warming of 1.5°C*, which attracted great attention from governments, experts and the public. Positive measures have been taken worldwide to cope with climate change risks, such as the 2016 Paris Agreement signed by 178 contracting parties, which outlines unified actions for all countries to take in addressing global climate change.

In addition, the *Blue Book on Climate Change in China 2021* observed that China is one of the most sensitive and significant areas affected by global climate change. Hence, the Chinese government has promulgated a double strategy to meet two carbon targets: that is, the 'carbon peak' and 'carbon neutral' targets. It is challenging for Chinese enterprises to meet the mandatory 'double carbon' global climate risk target; however, the target also provides opportunities. Therefore, achieving high-quality development and improving the security of people's livelihood, in addition to maintaining carbon peak and carbon neutral simultaneously, has become an important problem worldwide. Accordingly, the impact of climate change at the microenterprise level also requires in-depth research.

Some scholars have discussed the macroeconomic effects of climate change, such as the effect of the increase in average temperature on agriculture (Schlenker et al., 2005; Schlenker and Roberts, 2009; Zhang et al., 2017), industrial output or economic growth (Dell et al., 2012), health or mortality (Heutel et al., 2021), international trade (Jones and Olken, 2010), labor or total factor productivity (Letta and Tol, 2019; Patle et al., 2020), and have found that all factors have a negative impact. However, few have considered the impact of climate change on microenterprises' economic activities. Climate change has brought many levels of risk to countries and enterprises, including physical risk (e.g., the Zhengzhou flood disaster, severe storms, droughts and extremely high temperatures). Government policies related to climate change have been established (e.g., expected energy efficiency standards, carbon trading schemes and the double carbon policy) in addition to regulatory risks (e.g., green reputation, changing consumer behavior and increasing humanitarian needs). These differing risks have significant impacts on enterprises' daily business activities, such as procurement, production, sales and value chain creation, which are further affect enterprises' overall competitiveness.

Growth in operating income shows that the scale of the enterprise is expanding, which can more effectively reflect the senior executives' operational behavior and is the starting point of all enterprises' business activities (Dechow and Dichev, 2002). Unlike profit, operating income is not easily manipulated and the index of operating income is often more dependable. In enterprise valuation, the price-to-sales ratio is more objective than the price-to-earnings ratio (Du and Ping, 2005). Climate change affects enterprises' production and operational activities; therefore, it is likely to also cause fluctuations in enterprises' sales revenue. Using factory-level

data from American enterprises, however, Addoum et al. (2020) did not find that extreme high temperatures were related to factory productivity and sales income. Addoum et al. (2020) speculated that this was because enterprises in developed countries have easy access to enough resources to withstand temperature changes. As the largest developing country in the world, China has a relatively tight energy supply compared with Western developed countries and enterprises have relatively limited access to cheap resources. Does climate change impact Chinese enterprises' sales ability? This is the core problem of our paper.

First, climate change generally affects the productivity and production time of employees in production and sales departments, which subsequently affects their enterprises' production and sales capacity. The occurrence of extreme climate events further increases the uncertainty of enterprises' internal and external environment, including their operational risk, which subsequently reduces their sales ability. Second, due to increasingly severe climate change, local governments in China tend to adopt market-distorting policies and measures because of the external pressure from the central government to reduce emissions and their governors' motivation to pursue promotion, such as supplying electricity at different times during extreme temperatures, forced power rationing and implementing differentiated electricity prices. These actions increase enterprises' production and management costs, affect enterprises' production efficiency and reduces their sales ability. Third, if customers realize that the regions where enterprises are based are at greater risk of climate change, they will reduce their purchase quantities and purchase products from enterprises in regions with a lower risk of climate change, which will directly affect enterprises' product sales ability. Therefore, it is theoretically possible to study the impact of climate change on enterprises' sales ability.

Climate change occurs in the natural environment, which is generally an external consideration for enterprises. Managers cannot control the time and place of climate change, which avoids the issue of reverse causality problems. In addition, climate change and extreme weather events are random and complex; therefore, they are very difficult for enterprises to predict. Enterprises cannot easily change their production location in anticipation of climate change because of the high cost of moving. As a result, most enterprises passively accept climate shocks and reduce their underestimation of the impact of climate risk following relocation. Hence, we can explore the relationship between climate change and enterprises' sales ability by empirical method and draw the corresponding conclusions.

Based on local cities' climate change data and the operating income data of Chinese listed enterprises from 2008 to 2019, we study the impact of climate change on enterprises' sales ability and its subsequent influence on their sales revenue from three dimensions: inside enterprises, the supply side

and the demand side. The results show that climate change reduces enterprises' sales revenue. From the internal perspective of enterprises, climate change reduces production efficiency, increases management costs and the impact on the cost of sales is not obvious. From the demand side, climate change increases business risks, reduces transactions between large customers and enterprises and reduces the share of sales from large customers but has no obvious impact on small customers. On the supply side, climate change reduces business credit levels, which in turn reduces sales revenue. A heterogeneity analysis shows that the impact of climate change on sales revenue is more obvious in private enterprises, enterprises with weak internal controls and enterprises in central and western regions of China.

This paper contributes to the literature in the following aspects. (1) Enterprises' uncertainty risks were previously mainly focused on the institutional or market environment. Following the literature on China's capital market, we find that climate risks, as an important aspect of business risks, also affect enterprises' micro-business behavior. (2) We break through the traditional framework of economic policy and enterprise systems to show that the climate change has a significant impact on enterprises' sales ability. This finding not only deepens our understanding of enterprises' decision-making about climate risk, but also enriches the product marketing literature. (3) Climate change studies have been mainly conducted at the macro level; however, we expand research on the economic impact of climate change to the microenterprise level. Huang et al. (2018) empirically observed the impact of climate change on enterprises' financing choices and found that the vendor-customer channel facilitates enterprises' product sales ability, which verifies the transmission mechanism of climate change affecting product sales ability. This finding not only deepens our theoretical understanding of the economic consequences of climate change at the micro level, but also provides the necessary theoretical basis and experiential reference for reducing enterprises' overall risk.

In the following section, the results of our literature review are presented, in addition to a discussion of our proposed hypothesis. The research design is outlined in the third section, while the empirical results are given in the fourth section. The mechanism analysis and heterogeneity analysis are discussed in the fifth section. Finally, the sixth section presents our conclusions and suggestions.

Literature review and hypothesis

Economic consequences of climate change

Multiple economic consequences of climate change have been explored in the literature. Climate can have a negative impact on the macro economy. For example, Nordhaus (2006)

showed that climate was one of the key variables to explain the differences in per capita income between Africa and richer parts of the world. In addition, temperature is one of the main measures of climate change. Dell et al. (2009) found that countries with higher average temperature had lower per capita income level and growth rate. Hsiang (2010) studied 28 Caribbean Basin countries and observed that high temperatures had a negative impact on economic output and labor productivity, and the impact on non-agricultural industries was higher than that on agricultural industries. Dell et al. (2012) also found that per capita income in developing countries dropped by 1.4 percentage points for every 1°C increase in average temperature. Bansal and Ochoa (2011) illustrated the negative impact of temperature on economic and stock market growth, where the impact on low latitude countries was greater than that in high latitude countries. In 2018, the IPCC issued the *Special Report on Global Warming of 1.5°C*, which noted that the increasing global average temperature and sustained climate change will have a negative impact on economic activity and output. Burke et al. (2015) estimated that continuous global warming may reduce the world's average income by 23% by 2100. In addition, Thamotheram (2015) showed that global stock portfolios would lose 5–20% of their value if the temperature increased by $\geq 4^\circ\text{C}$.

Climate change and enterprises' sales ability

The growth of operating income often means the expansion of the scale of the enterprise, which can more effectively reflect the operating conditions of the enterprise, and is the starting point for all business activities of the enterprise (Dechow and Dichev, 2002). Revenue depends on employees who are affected by climate change. In addition, high-temperature weather reduces enterprise investment, productivity, household income and total economic output (Xie, 2017; Traore, 2018; Zhang et al., 2018; Li et al., 2021; Somanathan et al., 2021).

Climate change has a negative impact on enterprises' internal production and business activities. First, climate change may reduce worker productivity. Employees' cognitive and physical performance sustain negative effects when affected by extreme temperatures (Pilcher et al., 2002; Seppanen et al., 2006). Both cognitive decline and physical discomfort reduce productivity. Second, extreme temperatures reduce employees' available working hours compared with comfortable temperatures. Severe weather conditions reduce employees' productive motivation. In addition, If the working hours remain the same, it is easier for the physical capacity of employees to reach the limit in extreme weather conditions, so that companies have to reduce the number of hours employees work, so climate change will have a persistent negative impact on working hours (Graff Zivin and Neidell, 2014). In a study of Indian enterprises,

Somanathan et al. (2021) found that hot weather decreased employees' productivity and increased their absenteeism rate. Employees are a valuable resource for enterprises; therefore, declines in employee productivity and working hours will affect enterprises' normal operations and reduce production.

In addition, climate change may force enterprises to place more stringent limits on their energy use. After experiencing increasingly severe ecological problems, the Chinese government has promulgated major strategies, such as constructing an ecological civilization and setting 'double carbon' emission reduction targets. To achieve the established emission reduction and energy saving goals, however, local governments must conduct administrative activities, such as rationing power, because of the pressure from the central government to be held accountable during performance appraisals and their governors' pursuit of promotion.

Considering the dominant high polluting and high energy consumption development model used in the Chinese manufacturing industry, the original intention underlying the 'double carbon' targets is to not only introduce green management practices and improve the natural environment but also promote the transformation of development models in 'dual high' industries, such as those with high energy consumption and high pollution. However, local governments' poor decisions tend to have a negative impact on enterprises' daily production and operations, in addition to local residents' daily life. In addition to its negative impact on employee productivity and energy supply, climate change increases enterprises' production and management costs. Mishra and Singh (2010) and Pechan and Eisenack (2014) found that electricity prices (water supply) would increase (decrease) in extremely high temperatures, which would increase enterprises' production costs. To maintain temperatures in the workplace at an appropriate level during extremely high or low temperatures and reduce the impact on production and operations, enterprises must increase their air-conditioning expenditure, in addition to providing cooling or warming supplies to their production and management departments. Electricity prices may also rise during extreme temperatures, which further increases production and management costs. The higher costs of temperature management reduce enterprises' cash flow and adversely affect their internal production and operational activities. In short, climate change reduces employee productivity and increases energy consumption, production costs and administrative expenses, which subsequently decreases enterprises' production and operational capacity and ultimately has a negative impact on their sales ability.

Suppliers' extension of business credit to enterprises also decreases following climate change because extreme temperatures increase the uncertainty of enterprises' production and operations compared with normal climate conditions. Thus, climate change damages enterprises' ability to operate and increases their management risk, which subsequently

reduces their bargaining power and commercial credit with their suppliers. If the climate changes drastically, suppliers may consider that they have increased operational risks and subsequently reduce their cash discounts and other credit policies to encourage their buyers to pay in advance. Thus, climate change has a negative impact on enterprises' suppliers, that is, their procurement business. First, enterprises must pay their suppliers earlier. Second, the suppliers' discount rates enjoyed by enterprises decrease, which increases enterprises' production costs and weakens their sales ability. Therefore, climate change reduces enterprises' sales revenue.

Li et al. (2021) showed that high temperatures have a negative impact on enterprises' export quantity. First, the inconvenient environmental conditions for transportation induced by climate change have a negative impact on customers' purchase and payment intentions. During extreme temperatures, customers will reduce their travel and purchase expenditure. These lower purchase intentions will reduce enterprises' sales income. Moreover, climate change will lead customers stickiness decrease when the customers perceive that enterprises are at great management risk due to the high climate risk. These customers will change their purchase decisions in response to the higher climate risk in the enterprises' area and avoid purchasing the enterprises' products, which will reduce these enterprises' sales revenue.

Second, climate change will also reduce sales department employees' enthusiasm, which will have a negative impact on their enterprises' sales. Thus, climate change directly reduces enterprises' sales revenue by reducing their customers' purchase intentions and sales employees' enthusiasm. Hence, climate change indirectly weakens enterprises' sales ability by reducing their production and operational capacity and the level of commercial credit they can receive, which negatively affects their sales revenue directly by reducing their customers' purchase intentions and payment ability, in addition to sales employees' enthusiasm.

Based on the above analysis, we propose the following hypothesis:

H1: Climate change has a negative impact on enterprises' sales ability.

Climate change is usually quite slow; therefore, its short-term effects may not be directly observed in business operations or the market environment. However, the warming climate further aggravates the risk of extreme weather and climate events (CMA Climate Change Centre, 2021). In addition, China's climate risk index is rising. In 2020, the global average temperature was 1.2°C higher than the pre-industrial level. Although the development of modern industrial civilization greatly accelerated the rate of climate change, the extent of temperature change is still relatively small and it is difficult for residents and businesses to notice any significant change

over time. As noted above, while scholars have extensively documented the economic impacts of climate change at the business level, it remains unknown whether slow climate change significantly affects enterprises' short-term sales ability.

Moreover, business operators, suppliers and customers may not consider the impact of climate risk (Andersson et al., 2016; Barnett, 2019); therefore, climate change has a very weak impact on enterprises' short-term production, operations and sales. Even when extreme weather events become more intense, managers may still focus on their short-term financial performance because of the impact on stakeholders (such as customers and employees). Therefore, managers tend to ignore the long-term economic impact at the operating level because it is difficult for climate change to have a severe short-term effect on their business. Managers may not consider the natural environment and do not take measures to deal with climate change risks; therefore, they will not consider the impact of climate risk on their stakeholders (e.g., employees, suppliers, and customers). In addition, managers may not consider the economic consequences of differences in climate risk in different regions in their decision-making practices; therefore, climate risk does not influence enterprises' sales ability. Thus, we obtain our second hypothesis:

H2: Climate change has no effect on enterprises' sales ability.

Research design

Sample selection and data sources

Using climate change data from local cities, we select Chinese listed enterprises from 2008 to 2019 as our research

sample. We screen the initial sample as follows. First, we exclude financial, special treatment (ST) and particular transfer (PT) enterprises. In the literature, ST refers to enterprises experiencing abnormal financial conditions. PT refers to a special transfer service designed to provide a distribution channel for suspended stocks. Second, to avoid the influence of extreme values on our research conclusions, we reduce all continuous variables by 1% in the upper and lower quartiles. We obtain climate data from the Daily Data Set of China Surface Climatic Data collected from 842 datum and general surface meteorological observation stations operated by the National Meteorological Information Centre. We also obtain other financial data from the China Stock Market and Accounting Research database.

Model design and definition of the main variables

To test the above research hypotheses, we refer to Zhang et al. (2017) in constructing the following empirical model:

$$Lnincome = \beta_0 + \beta_1 Detatem + \sum Controls + \varepsilon$$

where an enterprise's product sales ability (*Lnincome*) is the natural logarithm of sales revenue. *Detatem* is the independent variable for climate change. Climate warming has the biggest impact on the natural ecosystem; therefore, climate change is measured by climate warming (Montzka et al., 2011). Following Deschenes and Greenstone (2007), we use the absolute value of the temperature difference over 3 years as the measurement value. The calculation formula for *Detatem* is the absolute value of the average temperature of each prefecture-level city in the current year after subtracting the average temperature of the past 3 years (Wang and Chen, 2014).

TABLE 1 Variable definitions.

Type	Variable	Description	Declaration
Dependent variable	<i>Lnincome</i>	Enterprise performance in the product market	The natural log of an enterprise's sales revenue
Independent variables	<i>Detatem</i>	Climate change	The absolute difference between the annual mean temperature and the mean of the past 3 years
Control variables	<i>SA</i>	Financing constraints	annual enterprise SA index
	<i>SIZE</i>	Scale of the enterprise	The natural log of an enterprise's total assets
	<i>BTMA</i>	Book-to-market ratio	The ratio of total assets to market value
	<i>CH</i>	Internal ownership concentration	Total shareholding ratio of the board of directors
	<i>Lev</i>	Debt levels	Total assets/total liabilities
	<i>CHAIR_CEO1</i>	The chairman and CEO are the same person	For a dummy variable, the value is 1; otherwise, the value is 0
	<i>ROA</i>	Enterprise profitability	Net interest rate on total assets in year <i>t</i>
	<i>Tobin_Q</i>	Enterprise performance	An enterprise's Tobin's Q-value
	<i>AGDP</i>	Regional economic level	Per capita gross domestic product (GDP) of an enterprise's location
	<i>FIC</i>	Proportion of foreign investment	Ratio of foreign investment to regional GDP

Table 1 reports the variable definitions. At the enterprise level, the control variables include the financing constraints (SA); enterprise size (SIZE), which is measured by the natural logarithm of total assets; book-to-market ratio (BTMA); directors' shareholding ratio (CH); the debt level of the enterprise (Lev); CHAIR_CEO is set to 1 if the chairman and CEO are the same person, and otherwise 0; return on assets (ROA); Tobin_Q indicates the Tobin's Q-value of the enterprise. At the regional level, the control variables include regional per capita gross domestic product (AGDP); and the proportion of foreign investment (FIC). In addition, we control for year and industry fixed effects.

Empirical results

Descriptive statistics

Table 2 reports the descriptive statistics of the variables. From 2008 to 2019, the mean *Lnincome* is 21.34 and the

median is 21.21, indicating that the income of Chinese listed enterprises generally changes over time. The mean value of *Detatem* is 0.34, which reflects an annual average temperature change of 0.34°C in Chinese cities. The average SA index of Chinese listed enterprises is -3.71, ROA is 4%, Lev is 45% and BTMA is 0.61. About 75% of the enterprises' chairman and CEO in our sample are the same person.

Correlation analysis

Table 3 presents the correlation coefficient matrix for the main variables. As shown in **Table 3**, the correlation coefficient between *Lnincome* and *Detatem* is significant and negative, indicating that the greater the climate change, the lower the enterprise's sales income, which preliminarily verifies *H1*. Considering the control variables at the enterprise level, SA and *Tobin_QA* are negatively correlated with sales revenue, while ROA, SIZE, Lev, and BTMA are positively correlated with sales

TABLE 2 Descriptive statistics.

Variable	N	Mean	SD	Min	Max	p25	p50	p75
<i>Lnincome</i>	26,794	21.340	1.550	17.330	25.750	20.300	21.210	22.240
<i>Detatem</i>	26,804	0.340	0.250	0.000	1.150	0.160	0.280	0.470
<i>AGDP</i>	26,583	14.300	11.870	1.280	50.460	5.660	11.140	18.630
SA	26,812	3.710	0.260	4.320	2.990	3.880	3.710	3.540
ROA	26,812	0.040	0.060	0.290	0.200	0.010	0.040	0.070
SIZE	26,812	22.060	1.430	19.250	27.040	21.050	21.850	22.820
CHAIR_CEO1	26,388	0.750	0.430	0.000	1.000	1.000	1.000	1.000
CH	25,050	7.600	13.630	0.000	54.210	0.000	0.000	10.410
FIC	24,768	12.220	1.680	6.940	14.700	11.280	12.680	13.420
Lev	26,812	0.450	0.220	0.050	0.980	0.270	0.440	0.610
<i>Tobin_Q</i>	26,812	2.100	1.450	0.890	9.890	1.250	1.640	2.370
BTMA	26,812	0.610	0.240	0.100	1.130	0.420	0.610	0.800

TABLE 3 Correlation coefficients.

	<i>Lnincome</i>	<i>Detatem</i>	<i>AGDP</i>	SA	ROA	Size	CHAIR_CEO	CH	FIC	LEV	<i>Tobin_QA</i>	BTMA
<i>Lnincome</i>	1											
<i>Detatem</i>	-0.025***	1										
<i>AGDP</i>	0.058***	-0.142***	1									
SA	-0.054***	0.104***	-0.075***	1								
ROA	0.086***	-0.009	0.021***	0.050***	1							
SIZE	0.868***	-0.027***	0.080***	-0.046***	0.009	1						
CHAIR_CEO	0.171***	0.039***	-0.138***	-0.065***	-0.046***	0.178***	1					
CH	-0.231***	-0.057***	0.171***	0.160***	0.139***	-0.256***	-0.318***	1				
FIC	0.093***	-0.051***	0.516***	-0.0100	0.052***	0.118***	-0.054***	0.092***	1			
LEV	0.418***	0.042***	-0.051***	-0.066***	-0.384***	0.448***	0.168***	-0.313***	-0.039***	1		
<i>Tobin_Q</i>	-0.412***	0.014**	0	0.046***	0.029***	-0.435***	-0.060***	-0.007	0.001	-0.170***	1	
BTMA	0.504***	-0.016**	-0.001	-0.021***	-0.113***	0.576***	0.107***	-0.086***	0.008	0.311***	-0.798***	1

*** and ** denote significance at the 1, 5, and 10% levels, respectively.

revenue. At the regional level, *AGDP* and *FIC* are positively correlated with sales revenue.

Regression analysis

Columns (1) to (3) of **Table 4** show the regression results of no control variable, adding control variables but no industry and time fixed effects and all control variables are added. The robust standard errors is in brackets. *Detatem* has a significant and negative correlation with *Lnincome*, which indicates that when climate change is more intense and the average temperature changes, enterprises' sales ability is affected and their sales income decreases with a corresponding deterioration of their product performance in the market. These results support *H1*. In terms of the control variables, when an enterprise combines two businesses, the smaller the *SA* index, the larger the size, the lower the shareholding ratio of the board of directors, the higher the profit margin on total assets, the higher the asset–liability ratio

TABLE 4 Impact of climate change on enterprises' sales revenue.

	(1) <i>Lnincome</i>	(2) <i>Lnincome</i>	(3) <i>Lnincome</i>
<i>Detatem</i>	−0.158*** (0.000)	−0.040** (0.046)	−0.056*** (0.002)
<i>AGDP</i>		−0.001 (0.122)	0.001 (0.108)
<i>CHAIR_CEO</i>		0.044*** (0.000)	0.051*** (0.000)
<i>SA</i>		−0.061*** (0.002)	−0.062*** (0.001)
<i>SIZE</i>		0.884*** (0.000)	0.991*** (0.000)
<i>CH</i>		−0.001*** (0.002)	−0.002*** (0.000)
<i>ROA</i>		2.984*** (0.000)	2.813*** (0.000)
<i>FIC</i>		−0.002 (0.605)	0.016*** (0.000)
<i>LEV</i>		0.724*** (0.000)	0.830*** (0.000)
<i>Tobin_Q</i>		−0.096*** (0.000)	−0.062*** (0.000)
<i>BTMA</i>		−0.325*** (0.000)	−0.250*** (0.000)
Year	No	No	Yes
Ind	No	No	Yes
_cons	21.390*** (0.000)	1.553*** (0.000)	−1.119*** (0.000)
<i>N</i>	26,786	22,691	22,691
<i>Adj. R</i> ²	0.001	0.775	0.844

*** and ** denote significance at the 1, 5, and 10% levels, respectively.

TABLE 5 Regression results when using the extreme climate measure.

	(1) <i>Lnincome</i>	(2) <i>Lnincome</i>	(3) <i>Lnincome</i>
<i>Frel</i>	−0.001*** (0.002)	−0.002** (0.000)	−0.002*** (0.000)
<i>SA</i>		−0.048** (0.031)	−0.048** (0.020)
<i>ROA</i>		3.008*** (0.000)	2.866*** (0.000)
<i>SIZE</i>		0.882*** (0.000)	0.980*** (0.000)
<i>Chair_CEO</i>		0.047*** (0.000)	0.055*** (0.000)
<i>CH</i>		−0.002*** (0.000)	−0.002*** (0.000)
<i>Tobin_Q</i>		−0.093*** (0.000)	−0.058*** (0.000)
<i>BTMA</i>		−0.313*** (0.000)	−0.228*** (0.000)
<i>Lev</i>		0.757*** (0.000)	0.886*** (0.000)
<i>AGDP</i>		0.001 (0.869)	0.001** (0.013)
<i>FIC</i>		−0.011** (0.010)	0.007** (0.035)
Year	No	No	Yes
Ind	No	No	Yes
_cons	21.434*** (0.000)	1.760*** (0.000)	−0.751*** (0.000)
<i>N</i>	26,812	26,812	26,812
<i>Adj. R</i> ²	0	0.784	0.851

*** and ** denote significance at the 1, 5, and 10% levels, respectively.

and the lower the Tobin's *Q*-value or book-to-market ratio, the higher the enterprise's sales revenue. The sign and significance of the correlation coefficients after controlling for year and industry fixed effects are consistent with these results.

Robustness tests

Alternative measures of climate extremes

Climate change currently causes two major problems for enterprises: an increase in average temperature and the increasing frequency of extreme weather. Therefore, we adopt a new climate change measurement index and use the number of days with extremely low temperatures in the current year in an enterprise's location (*Frel*) as the explanatory variable. The control variables and fixed effects in the model remain unchanged to ensure the robustness of the results. **Table 5** shows the empirical results, where the coefficient of *Frel* is significant and negative in Columns (1) to (3), indicating that enterprises' sales revenue decreases following an increase in extremely low temperatures and worsening climate change.

Impact of low-carbon city pilot policy on sales revenue

In 2010, China promulgated a low-carbon city pilot policy to deal with the impact of economic development on the ecological environment. In August 2010, eight cities joined the first batch of national low-carbon pilot cities. In November 2012, the National Development and Reform Commission named 28 low-carbon pilot cities. When waste gas and waste water emissions are strictly restricted, the climate environment is improved in low-carbon pilot cities, which has a positive impact on enterprises' sales revenue. Hence, we introduce the low-carbon city pilot policy as an exogenous shock in this paper. The value of *Pilot* is 1 if a city or province is a pilot area for the first two batches of pilot cities and otherwise 0. In addition, *Post* is a dummy variable before and after the pilot policy. The value of *Post* is 1 during the low-carbon city pilot period (i.e., after 2012) and 0 during the non-pilot period. Table 6 presents the empirical results.

In Table 6, the coefficient of *Pilot-Post* which means the interaction term between *Pilot* and *Post* is significant and positive, indicating that enterprises' sales revenue increases with climate improvement in low-carbon cities. The low-carbon pilot cities have effectively restrained climate change and significantly promoted growth in enterprises' sales revenue. This result supports the conclusion that climate change has a significant and negative correlation with enterprises' sales ability.

TABLE 6 Impact of low-carbon city pilot policy on enterprises' sales revenue.

	<i>Lnnincome</i>	
<i>Pilot-post</i>	0.041***	(0.004)
<i>Pilot</i>	−0.046***	(0.000)
<i>Post</i>	−0.160***	(0.000)
<i>AGDP</i>	0.001***	(0.002)
<i>SA</i>	−0.066***	(0.000)
<i>CHAIR_CEO</i>	0.050***	(0.000)
<i>SIZE</i>	0.986***	(0.000)
<i>CH</i>	−0.002***	(0.000)
<i>ROA</i>	2.919***	(0.000)
<i>FIC</i>	0.017***	(0.000)
<i>Lev</i>	0.889***	(0.000)
<i>Tobin_Q</i>	−0.047***	(0.000)
<i>BTMA</i>	−0.181***	(0.000)
<i>Ind</i>	Yes	
<i>Year</i>	Yes	
<i>_cons</i>	−1.074***	(0.000)
<i>N</i>	28,236	
<i>Adj. R²</i>	0.847	

*** and ** denote significance at the 1, 5, and 10% levels, respectively.

Impact of temperature variation difference on sales revenue

In this paper, we adopt a new climate change measurement index. We use the absolute value of the difference between the average temperatures of the current year and the past 4, 5, and 6 years as explanatory variables (*Detatem4*, *Detatem5*, and *Detatem6*, respectively). To ensure the robustness of the results, the control variables and fixed effects in the model remain unchanged. Table 7 shows the empirical results. In Table 7, Columns (1) to (3) show that regardless of which alternative method is used to measure climate change as the new explanatory variable, the coefficients of *Detatem4*, *Detatem5*, and *Detatem6* are significant and negative. This indicates that enterprises' sales ability decreases following the

TABLE 7 Impact of temperature variation difference on sales revenue.

	(1) <i>Lnnincome</i>	(2) <i>Lnnincome</i>	(3) <i>Lnnincome</i>
<i>Detatem4</i>	−0.061*** (0.001)		
<i>Detatem5</i>		−0.067*** (0.000)	
<i>Detatem6</i>			−0.073*** (0.000)
<i>AGDP</i>	0.001 (0.154)	0.001 (0.172)	0.001 (0.176)
<i>SA</i>	−0.062*** (0.001)	−0.062*** (0.001)	−0.062*** (0.001)
<i>CHAIR_CEO</i>	0.051*** (0.000)	0.051*** (0.000)	0.051*** (0.000)
<i>SIZE</i>	0.991*** (0.000)	0.991*** (0.000)	0.991*** (0.000)
<i>CH</i>	−0.002*** (0.000)	−0.002*** (0.000)	−0.002*** (0.000)
<i>ROA</i>	2.813*** (0.000)	2.813*** (0.000)	2.812*** (0.000)
<i>FIC</i>	0.017*** (0.000)	0.017*** (0.000)	0.017*** (0.000)
<i>Lev</i>	0.830*** (0.000)	0.831*** (0.000)	0.830*** (0.000)
<i>Tobin_Q</i>	−0.062*** (0.000)	−0.062*** (0.000)	−0.062*** (0.000)
<i>BTMA</i>	−0.250*** (0.000)	−0.250*** (0.000)	−0.250*** (0.000)
<i>Ind</i>	Yes	Yes	Yes
<i>Year</i>	Yes	Yes	Yes
<i>_cons</i>	−1.119*** (0.000)	−1.116*** (0.000)	−1.113*** (0.000)
<i>N</i>	22,691	22,691	22,691
<i>Adj. R²</i>	0.844	0.845	0.845

*** and ** denote significance at the 1, 5, and 10% levels, respectively.

aggravation of climate change, which is consistent with the main regression results.

Mechanism and heterogeneity analyses

Mechanism

According to the above theoretical analysis, we believe that the higher operational and financial risks caused by climate change reduce enterprises' production efficiency and credit level, leading to a reduction in enterprises' sales income. We now focus on the internal mechanism of the impact of climate change

on enterprises' sales revenue using three pathways: namely, enterprise, enterprise demand and enterprise supply.

As shown in the regression results of **Table 8**, the coefficient of *Detatem* in Column (1) is significant and negative, while that in Column (2) is negative but not significant. This indicates that the increase in temperature significantly reduces the share of sales from large customers, but has no significant impact on the share of sales from small customers. Increasing temperatures will cause huge business risks for enterprises and affect the transactions between enterprises and their large customers, which reduces the transaction share from large customers in addition to enterprises' sales revenue.

On the supply side, as shown in Column (3) of **Table 8**, the coefficient of *Detatem* is significant and negative, indicating that the increase in temperature significantly reduces enterprises' level of business credit, affects suppliers' provision of materials

TABLE 8 Regression results for the mechanism of action.

	Demand side		Supply side	Enterprise side		
	(1) Large customers	(2) Small customers	(3) Commercial credit	(4) Productivity	Cost of sales	Management fees
	<i>ln_{top}</i>	<i>ln_{untop}</i>	<i>detbc1</i>	<i>tfp_{lp}</i>	<i>sale</i>	<i>man</i>
<i>Detatem</i>	−0.070** (0.016)	−0.027 (0.435)	−0.005** (0.050)	−0.054*** (0.002)	−0.039 (0.202)	−0.027* (0.064)
<i>AGDP</i>	0.002*** (0.003)	−0.001 (0.952)	0.000*** (0.000)	0.002*** (0.000)	0.001* (0.088)	0.002*** (0.000)
<i>SA</i>	0.151*** (0.000)	0.071** (0.049)	0.011*** (0.000)	−0.055*** (0.003)	−0.139*** (0.000)	−0.054*** (0.000)
<i>CHAIR_CEO</i>	0.070*** (0.000)	0.015 (0.427)	0.002 (0.220)	0.022** (0.018)	−0.039** (0.016)	0.035*** (0.000)
<i>SIZE</i>	0.799*** (0.000)	0.980*** (0.000)	−0.006*** (0.000)	0.595*** (0.000)	0.925*** (0.000)	0.864*** (0.000)
<i>CH</i>	−0.003*** (0.000)	0.001 (0.643)	−0.001** (0.011)	−0.001 (0.265)	0.003*** (0.000)	0.002*** (0.000)
<i>ROA</i>	1.726*** (0.000)	3.199*** (0.000)	0.118*** (0.000)	2.989*** (0.000)	2.928*** (0.000)	0.109* (0.074)
<i>FIC</i>	0.027*** (0.000)	−0.009* (0.080)	0.004*** (0.000)	0.036*** (0.000)	0.015*** (0.002)	0.034*** (0.000)
<i>LEV</i>	0.641*** (0.000)	0.803*** (0.000)	0.213*** (0.000)	0.799*** (0.000)	0.290*** (0.000)	0.087*** (0.000)
<i>Tobin_Q</i>	−0.036*** (0.000)	−0.117*** (0.000)	−0.007*** (0.000)	−0.030*** (0.000)	−0.085*** (0.000)	−0.001 (0.757)
<i>BTMA</i>	−0.069 (0.222)	−0.186*** (0.006)	−0.006 (0.301)	−0.094*** (0.005)	−0.908*** (0.000)	−0.621*** (0.000)
<i>Ind</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>_cons</i>	−1.863*** (0.000)	−0.491** (0.038)	0.054*** (0.007)	0.689*** (0.000)	−2.622*** (0.000)	−0.863*** (0.000)
<i>N</i>	27,901	27,548	19,273	22,281	27,541	28,222
<i>Adj. R²</i>	0.561	0.555	0.300	0.712	0.536	0.790

***, **, and * denote significance at the 1, 5, and 10% levels, respectively.

and thus weakens enterprises' competitiveness in the product market and subsequently reduces their sales revenue.

As shown in Column (4) of Table 8, the coefficient of *Detatem* is significant and negative from the internal perspective of enterprises, which indicates that increasing temperatures significantly reduce enterprises' productivity. When the temperature rises, employees' work efficiency and working hours decrease. Column (4) also shows that climate change significantly increases enterprises' management and production costs and decreases their production efficiency and sales income.

Heterogeneity analysis

Climate change, ownership nature, and sales revenue

State-owned enterprises usually have important strategic positions and more external resources than private enterprises. In addition, state-owned enterprises' operating goals are more political than they are economic. When temperatures rise,

state-owned enterprises receive more government support and resources than private enterprises do. In addition, their suppliers and customers do not change significantly. Therefore, their sales are likewise not affected significantly. To test this conjecture, we divide the total sample into state-owned enterprises and private enterprises according to their equity and use Model (1) to conduct the respective regression analyses. Table 9 shows the results of the regression analyses.

In Column (2) of Table 9, for private enterprises, the coefficient of *Detatem* is significant and negative, indicating that climate change has a significant and negative influence on private enterprises' sales revenue. In contrast, for state-owned enterprises, the coefficient of *Detatem* is not significant in Column (1), indicating that climate change has no significant influence on state-owned enterprises' sales revenue. The combined results of Columns (1) and (2) indicate that climate

TABLE 9 Climate change, ownership, and sales revenue.

	(1) State-owned enterprises	(2) Private enterprises
<i>Detatem</i>	−0.020 (0.519)	−0.093*** (0.000)
<i>AGDP</i>	−0.004*** (0.000)	0.002*** (0.000)
<i>SA</i>	0.203*** (0.000)	0.083*** (0.002)
<i>CHAIR_CEO</i>	0.010 (0.692)	0.028** (0.035)
<i>SIZE</i>	0.962*** (0.001)	0.976*** (0.001)
<i>CH</i>	−0.009 (0.200)	0.001 (0.540)
<i>ROA</i>	2.420*** (0.000)	3.350*** (0.000)
<i>FIC</i>	0.009* (0.077)	−0.006 (0.163)
<i>Lev</i>	0.665*** (0.000)	0.683*** (0.000)
<i>Tobin_Q</i>	−0.122*** (0.000)	−0.102*** (0.000)
<i>BTMA</i>	−0.654*** (0.000)	−0.293*** (0.000)
<i>Ind</i>	Yes	Yes
<i>Year</i>	Yes	Yes
Coefficient difference test	3.18*	
_cons	1.164*** (0.000)	0.101 (0.534)
<i>N</i>	9,333	12,952
<i>Adj. R²</i>	0.779	0.744

***, **, and * denote significance at the 1, 5, and 10% levels, respectively.

TABLE 10 Climate change, regional economy, and sales revenue.

	(1) Eastern China	(2) Central and western China
<i>Detatem</i>	−0.006 (0.820)	−0.071** (0.012)
<i>AGDP</i>	−0.001 (0.621)	−0.015*** (0.000)
<i>SA</i>	−0.062*** (0.004)	−0.042 (0.250)
<i>CHAIR_CEO</i>	0.063*** (0.000)	0.026 (0.169)
<i>SIZE</i>	0.966*** (0.000)	1.030*** (0.000)
<i>CH</i>	−0.001*** (0.002)	−0.005*** (0.000)
<i>ROA</i>	2.811*** (0.000)	2.668*** (0.000)
<i>FIC</i>	−0.005 (0.268)	0.027*** (0.000)
<i>Lev</i>	1.065*** (0.000)	0.508*** (0.000)
<i>Tobin_Q</i>	−0.045*** (0.000)	−0.078*** (0.000)
<i>BTMA</i>	−0.122*** (0.004)	−0.425*** (0.000)
<i>Ind</i>	Yes	Yes
<i>Year</i>	Yes	Yes
Coefficient difference test	2.87*	
_cons	−0.531*** (0.001)	−1.649*** (0.000)
<i>N</i>	14,652	8,039
<i>Adj. R²</i>	0.857	0.830

***, **, and * denote significance at the 1, 5, and 10% levels, respectively.

change has a greater impact on the sales ability of private enterprises than on that of state-owned enterprises.

Climate change, regional economy, and sales revenue

Enterprises in more economically developed regions are likely to be less affected by climate change than those in less economically developed regions because they have the resources and capabilities to withstand extreme weather events. At the same time, the ecological environment in central and western China is relatively fragile and the ability to cope with climate change is relatively weak, especially in western China. The ecological environment in the west has a poor congenital foundation and strong external interference. The vulnerability and damage degree of its ecological environment are still in a relatively severe stage. All of these factors magnify the

climate risks faced by enterprises in central and western China. Therefore, the negative impact of climate change on enterprises' sales revenue in central and western China should be greater than that in eastern China.

To test this conjecture, we divide the sample into eastern China and central and western China according to local enterprises' economic situation and use Model (1) to conduct the regression analyses. Table 10 shows the results. The coefficient of *Detatem* in central and western China is significant and negative, indicating that climate change has a significant and negative impact on enterprises' sales revenue in central and western China. However, the coefficient of *Detatem* in eastern China is not significant, indicating that the effect of climate change on enterprises' sales revenue in eastern China is not significant. The combined results of Columns (1) and (2) in Table 10 show that climate change has a greater impact on enterprises' sales ability in economically underdeveloped areas than in more economically developed areas.

TABLE 11 Climate change, internal controls, and sales revenue.

	(1) Enterprises with weak internal controls	(2) Enterprises with strong internal controls
<i>Detatem</i>	−0.070** (0.024)	−0.026 (0.313)
<i>AGDP</i>	0.001* (0.068)	0.001 (0.250)
<i>SA</i>	−0.059* (0.087)	0.060** (0.024)
<i>CHAIR_CEO</i>	0.041** (0.018)	0.064*** (0.000)
<i>SIZE</i>	1.009*** (0.000)	0.985*** (0.000)
<i>CH</i>	−0.001** (0.029)	−0.004*** (0.000)
<i>ROA</i>	1.950*** (0.000)	3.957*** (0.000)
<i>FIC</i>	0.019*** (0.000)	0.019*** (0.000)
<i>Lev</i>	0.545*** (0.000)	1.051*** (0.000)
<i>Tobin_Q</i>	−0.105*** (0.000)	−0.051*** (0.000)
<i>BTMA</i>	−0.385*** (0.000)	−0.111** (0.028)
<i>Ind</i>	Yes	Yes
<i>Year</i>	Yes	Yes
Coefficient difference test	1.05	
<i>_cons</i>	−1.401*** (0.000)	−0.771*** (0.000)
<i>N</i>	10,282	10,684
<i>Adj. R²</i>	0.783	0.866

***, **, and * denote significance at the 1, 5, and 10% levels, respectively.

Climate change, internal controls, and sales revenue

Compared with enterprises with weak internal controls, enterprises with strong internal controls have more timely and effective decision-making feedback and implementation during climate change events. In addition, enterprises' internal controls enable all employees to participate in corporate governance, which can effectively alleviate their multilayer agency problem and improve operating efficiency. Therefore, climate change may have a stronger impact on the sales revenue of enterprises with weak internal controls than those with strong internal controls. Table 11 shows the empirical regression results. We divide the sample into two groups according to the degree of internal control. In the subsample of enterprises with weak internal controls, the coefficient of *Detatem* is significant and negative, while that for enterprises with strong internal controls is not significant. The combined results of Columns (1) and (2) show that climate change has a greater negative impact on enterprises with weak internal controls than on enterprises with strong internal controls.

Conclusion and implications

Conclusion

Following the aggravation of climate change and the frequent occurrence of extreme climate events, the impact of climate change has become a critical issue that cannot be ignored in academic and practical circles. Many conclusions have been drawn on the macroeconomic impact of climate change, but there is little discussion of the microeconomic impact of climate change, and empirical research at the enterprise level is still in its infancy. China is currently the world's largest

industrial country; thus, it is pursuing carbon peak and carbon neutral policies vigorously. These ‘double carbon’ targets help China to transform its economy toward green and sustainable development and promote the construction of a beautiful China and global climate governance. These efforts fully demonstrate that China is deeply involved in the fight against global climate change. Maintaining ecological security and achieving green development is currently a challenging socio-economic consensus globally. In China, it is difficult to achieve a balance between environmental governance and economic operations, in addition to simultaneously promoting carbon emission reduction targets and economic transformation processes, especially in combination with China’s strategic task of high-quality economic development and construction of an ecological civilization. Therefore, this paper provides important findings for the literature on the economic impact of climate change on microenterprises.

We use Chinese listed enterprises from 2008 to 2019 as a sample and conduct an empirical study controlling for industry and time fixed effects in the model. We find that climate change has a significant and negative impact on enterprises’ sales ability. We use difference-in-differences and variable substitution to demonstrate the robustness of our research findings. Furthermore, the mechanism of the impact of climate change on enterprises’ sales ability is analyzed from three dimensions: that is, inside enterprises, the demand side and the supply side. We also find that climate change has a greater impact on private enterprises than on state-owned enterprises. In addition, the impact of climate change on enterprises in less developed areas is greater than that in developed areas. Finally, the impact of climate change on enterprises with weak internal controls is greater than for enterprises with strong internal controls.

Implications

As one of the countries with the largest variety, intensity and frequency of climate disasters in the world, China faces a particularly prominent risk of climate change. Climate change may affect China’s ecological environment, economic development, national security, and even society stability. China is facing challenges in addressing climate change and has made many efforts to control it. When determining major national strategies and overall layout of the construction of ecological civilization, China has taken carbon peaking and carbon neutrality into account and promote the “dual carbon” work in all areas of society. On the one hand, China has gradually reduced coal consumption and actively promoted the transformation of its energy structure. By 2020, China’s share of coal in energy consumption has fallen from nearly 70% in 2012 to 57%. On the other hand, China has launched online trading in the carbon market, which has played an optimal

role in the allocation of energy resources. In the same year, the Ministry of Ecology and Environment of the People’s Republic of China promulgated the ‘*Administrative Measures for Carbon Emissions Trading*’ (Trial Implementation), officially launching China’s carbon market. Physical risks such as climate change (e.g., floods, droughts, severe storms, and extreme heat), policy changes and regulatory changes (e.g., corporate reputation), changes in consumer behavior and increased humanitarian needs will affect businesses, such as procurement, production, sales and more. Due to the randomness and complexity of climate change, companies are basically unable to avoid risk by predicting climate change, and can only passively accept climate change. In the long run, the comprehensive competitiveness is bound to be affected. Based on the above analysis, we made the following recommendations from the perspective of enterprise, society, and government.

Recommendations from the enterprise perspective

First, raising the awareness of climate change among managers. Enterprises should strengthen the training of managers on climate change, so that they can understand climate change issues and how to deal with relevant risk. Senior managers should establish a high degree of climate risk awareness and improve climate change response capabilities.

Second, improving the level of internal control of the enterprises. Climate change has adversely impacted the sales capacity of enterprises by affecting demand-side, supply-side and internal production and operation activities. Enterprises should improve the quality of internal control to reduce the adverse impact of climate change on enterprise sales.

Third, improving the technical level and establish emission reduction plans that balance the interest of enterprise and climate change risk. The enterprise should pay attention to relevant policies to address climate change at the national and even international levels. Under the guidance of macro climate change measures, adopt new production models (e.g., research and development of low-carbon technologies in the production process, purchasing applicable low-carbon production technologies, etc.) and operating methods (e.g., expanding green industrial chains, integrating emerging low-carbon technologies markets etc.). Enterprise should optimize their production and operation structure, reduce production costs, and improve their comprehensive competitiveness.

Recommendations from social perspective

First, raising the awareness of Chinese residents on climate change issues. Propaganda related to climate change can be strengthened by printing brochures and setting up relevant websites. Residents should also actively participate in climate change governance and pay attention to climate change issues.

Second, improving the observation capability and meteorological service level of climate change. The

meteorological department needs to continuously improve the meteorological monitoring technology, provide more real, reliable and applicable meteorological data, and actively cooperate with local enterprises to develop new meteorological services (e.g., early warning of climate disasters, etc.) for them and provide effective support for them to cope with climate change.

Recommendations from government perspective

First, the government should improve the response mechanism to climate change and the rescue mechanism for enterprises under climate disasters, and coordinate the promotion of economic development and green governance. Local government needs to build a comprehensive climate change response mechanism as well as climate disaster prevention and control mechanism. They should strive to act in respond quickly before or at the early stage of meteorological disasters caused by climate change, and take necessary measures to minimize the impact to local enterprises and society. Local government in areas with high climate risk and economically underdeveloped areas should strengthen their awareness of green governance, establish the concept of green development, and establish climate change response mechanism.

Second, strengthening the awareness of cooperation, promoting interregional cooperation to cope with climate change. We find that the sales ability of enterprises in developed regions is less affected by climate change. On this basis, the developed areas can form a supporting mechanism with underdeveloped areas to strengthen cooperation and exchange between regional governments and provide resources and technologies to underdeveloped areas to deal with climate change. Only in this way can they maintain their own green development advantages while improving the ability of underdeveloped areas to cope with climate change.

Third, continue to promote and improve policies and actions related to carbon emission reduction. We confirm that low-carbon city pilots have a positive effect on reducing the economic impact of climate change, indicating that the “double carbon” goal is not only a major strategy for the construction of ecological civilization, but also a practical need to meet the demand of green development. Carbon Peak Action can reduce the adverse impact of carbon emission on residents’ daily life and natural environment, have a long-term positive impact on business operation. It can boost the comprehensive green transformation of economic and social development, provide a Chinese solution for achieving high-quality economic development and global green governance.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/supplementary material.

Author contributions

SY: conceptualization, methodology, and software. CC: data curation and writing—original draft preparation. SZ: visualization and investigation. PY: supervision and writing—reviewing and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

PY was employed by Shenzhen Ji Yatou Biotechnology Co., Ltd.

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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The impact of government environmental attention on public health: Implications for corporate sustainable development

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As major contributors to air pollution, enterprises have a growing impact on the environment, which puts public health at risk and requires urgent government intervention. This study constructs a government environmental attention variable via textual analysis of Chinese government work reports from 2004 to 2017, and examines the impact of government environmental attention on public health. We find that local government environmental attention has a significant and positive impact on public health. Our mechanism analysis suggests that government environmental governance investment acts as an important mediating channel in transferring the impact of government environmental attention on public health. Moreover, we find that the impact of government environmental attention on public health is more pronounced in Central and Western China, in low-openness regions, and after the incorporation of environmental performance in the cadre evaluation system in 2006. Overall, our study links micro-level environmental issues with macro-level governmental behaviors, providing a new perspective for future research on the influencing factors of public health and practical implications for corporate sustainable development.

KEYWORDS

government environmental attention, public health, textual analysis, government work report, environmental governance

1 Introduction

Environmental pollution has become a major threat to human survival (Schwarzenbach et al., 2010; van Heezik and Brymer, 2018; Pérez Ibarra et al., 2020). According to the National Bureau of Statistics of China, China's sulfur dioxide, nitrogen oxides, and particulate matter emissions in 2020 reached 3.182 million tons, 11.817 million tons and 6.134 million tons, respectively, with a proportion of 86.46%,

44.42% and 85.07% from the industrial production. As the primary pollutant emitters and resource consumers, businesses have an inescapable responsibility to address environmental problems. Studies show that the deteriorated environment has shortened the average global life expectancy (Ebenstein et al., 2015), posing a severe threat to public mental and physical health (Cesaroni et al., 2012; Lelieveld et al., 2015; Cohen et al., 2017). Therefore, firms, as the building blocks of economic growth, should establish an environmental governance accountability mechanism and actively engage in the green transformation to alleviate environmental and public health problems.

However, firms are not carrying out their fair share of social responsibility due to free-riding behaviors and conflict between economic and social costs. Environmental governance ought not to rely solely on voluntary actions by businesses and individuals; the government should play an active role (Duan et al., 2020; Bansal et al., 2021; Tian et al., 2020). Specifically, governments can improve environmental governance performance through the implementation of environmental protection policies and regulations (Magnani, 2000; Biresselioglu and Demir, 2021; Kang et al., 2022), environmental governance investments (Ercolano and Romano, 2018), and regional joint prevention and control mechanisms (Yang, 2016). Since 2002, the Chinese government has promulgated a number of environmental regulations and policies to balance economic development with environmental costs (Li et al., 2021; Wan et al., 2021; Zhai et al., 2022), leading to dramatic improvement in the country's environmental quality. In 2019, the average percentage of days with good air quality in China's 337 cities reached 82%. China's environmental regulation and governance are becoming increasingly stringent in recent years (Xue et al., 2021; Liu et al., 2022). For example, the central government added local environmental performance into the cadre evaluation system in 2006, creating incentives for local officials to raise their environmental awareness and improve environmental governance practices (Yang et al., 2020). Also, during the ongoing COVID-19 pandemic, China made a commitment to reach a carbon peak by 2030 and carbon neutrality by 2060 (Tian et al., 2022).

The annual government work report—a policy document that reviews local government performance over the previous year and outlines future work plans—reflects the allocation of government attention (Wen, 2014). Attention refers to the psychological activity in which the subject consciously focuses on a certain thing (Ocasio, 2011).

Jones (1994) introduced the concept of attention into the research area of government behavior and proposed an attention-driven model of policy choice. This psychological model provides a new study angle on governmental behavior by arguing that the priority of government policy shifts in response to the changes in government attention. Because government is the principal executive of national governance and social administration, the allocation of government attention reflects the priority in public affairs (Boydston et al., 2014). With

limited attention, the choice of government behavior depends on matters attracting the most attention (Ocasio, 2011). Thus, the allocation of government attention in specific social areas requires further study.

Prior research has used government work reports to measure government attention. For example, Wen (2014) employed textual analysis of government work reports to measure government attention to public services. Similarly, Wu and Tang (2019) employed textual analysis of central government work report from 1978 to 2018 to measure the proportion of central government attention to the ageing problem. However, neither of them addressed the question of whether government attention is translated into practice. Among the few existing studies, Shi et al. (2019) examined the impact of provincial government work reports on substantive environmental investments by analyzing their discourse on environmental protection. But the impact of government attention on people's well-being is still scarce (Diener and Seligman, 2004).

In summary, we find that, first, most government attention-related studies focus on attention measurement, and few investigated whether government attention is translated into practice. Second, research on the impact of government attitudes and behaviors on public health is lacking. Finally, the mechanism through which governmental environmental attention affects public health should be explored. Therefore, the study on whether and how government environmental attention affects public health is vital to the public health research and environment psychology (Navarro et al., 2020).

In this paper, we choose China as the research setting to examine the relationship between government environmental attention and public health for two reasons. First, in recent years, the conflict between the ecological environment and economic development has grown more pronounced in China in recent years, and it is crucial to address the worsening environmental pollution and improve people's well-being in order to meet both the demand of people for a better life and the shift in the mode of economic development. Second, because the Chinese government plays a predominant role in the economy and performs a range of functions, such as decision-maker, supervisor, and governor, government attention and actions play an important role in public issues like improving environmental quality (Jiang et al., 2021; Wang et al., 2021). Therefore, using text mining to construct the government environmental attention variable, we select local government work reports from 31 provinces in Mainland China from 2004 to 2017 as the research object to empirically examine the relationship between government environmental attention and public health. The results show that government environmental attention significantly and positively affects public health. In addition, our mechanism analysis indicates that government environmental attention can improve public health through increased environmental governance investment. These findings remain robust after replacing explanatory variables

and mitigating endogeneity concerns. Additional analyses reveal that the impact of government environmental attention on environmental governance investment is significantly positive in Central and Western China, in low-openness regions, and after the inclusion of environmental performance in the cadre evaluation system in 2006. As such, our study extends the government attention-driven policy choice model to environmental psychology research, which provides an empirical basis for translating government attention into practice and important implications for guiding firms to assume social responsibility and adhere to sustainable development.

The remainder of this paper is structured as follows. [Section 2](#) introduces the data source and research methodology. [Section 3](#) presents and interprets the empirical results. [Section 4](#) concludes the paper and proposes policy recommendations.

2 Materials and methods

2.1 Model setting

China has had rapid economic growth since the reform and opening up, but the environment has suffered tremendous damage. Environmental problems caused by large-scale industrial development, such as the loss of arable land, water pollution, and air pollution, are impeding China's sustainable development and posing a direct threat to public health (Lu et al., 2019; Tao et al., 2022). According to the report of the Second United Nations Environment Assembly (2018), environmental pollution is responsible for nearly a quarter of all deaths globally. Studies also show that continuous exposure to air pollution reduces life expectancy (Ebenstein et al., 2017). The Chinese government has made many efforts in response to the worsening environmental problems. To strengthen environmental governance, the central government incorporated local environmental performance into the cadre evaluation system in 2006. Given the government's critical role in environmental governance as well as public health, the primary goal of our paper is to investigate the impact of government environmental attention on public health.

This study examines whether government environmental attention affects public health using government work reports from different provinces in China, and further investigates whether government environmental attention has been translated into environmental governance investment, and if so, whether government investment in environmental governance has an impact on public health. To test the research questions, this paper develops three econometric models. In the baseline regression, we construct a government environmental attention variable from the frequency of environment-related words in the government work reports as the key explanatory variable to examine the relationship between

government environmental attention and public health. For the mediation analysis, we choose environmental governance investment as the mediating variable. We first test the relationship between government environmental attention and environmental governance investment, and then use government environmental governance investment as the key explanatory variable to investigate the impact of government environmental performance on public health based on the aggregate health production function.

2.1.1 Baseline model

Attention research mainly focuses on individual decision-making at a micro-level. However, in recent years, attention studies have begun to be broadly applied in government policymaking (Dai, 2017). The government plays a leading role in managing public affairs, where it allocates public resources based on public feedback (De Marchi et al., 2016). From a psychological perspective, government attention is a scarce resource as the government has to cope with an extensive and complicated collection of public information (Meng and Fan, 2021). As such, the government has to allocate limited attention resources to maximize public interests. Government attention is highly reflected in government work reports. Therefore, this paper uses text mining to quantitatively identify government environmental attention based on China's provincial government work reports. To investigate the relationship between government environmental attention and public health. Following Liu et al. (2017), we run a regression using the following two-way fixed effects specification:

$$\ln(\text{Health}_{it}) = \alpha_0 + \alpha_1 \ln(WF_{it}) + \alpha_2 Z_{it} + \text{YearFE} + \text{ProvinceFE} + \varepsilon_{it} \quad (1)$$

where i is the province, t is the year. *Health* is the dependent variable, indicating public health. *WF* is the frequency of environment-related words in the government work reports of each province each year, which measures local government environmental attention. Z denotes the control variables, including gross domestic production (GDP) per capita (*PGDP*), value of imports and exports (*Open*), proportion of urbanization (*Urbanization*), degree of aging (*Aging*), level of education (*Education*), level of medical advancement (*Medical*). In addition, since governors play a leading role in public policymaking, this paper also controls for the personal characteristics of provincial governors, including gender (*Gender*), education level (*Edu*), age (*Age*), and tenure (*Tenure*). ε_{it} is the error term. Finally, we control for year fixed effects (*Year FE*) and province fixed effects (*Province FE*).

2.1.2 Mediation model

In this section, we investigate the mediating role of government environmental governance in the relationship between government environmental attention and public

health. In response to the worsening environmental pollution, the Chinese government has been increasing its focus on environmental issues. First, government governance decisions are predicated on the allocation of government attention according to the attention-driven policy choice model proposed by Jones (1994). Therefore, driven by the increasing environmental attention, addressing environmental problems, although challenging, becomes a priority for government governance. Second, enhanced government environmental governance will reduce environmental pollution and improve environmental quality, therefore enhancing public health by reducing mortality from diseases linked to environmental pollution (Kelly and Fussell, 2015; Zhang et al., 2019) as well as psychologically influencing residents' subjective well-being (Xue et al., 2020; Zhao and Sun, 2020). Therefore, following the methodology for mediation analysis proposed by Preacher and Hayes (2008), we construct the framework of "government environmental attention → environmental governance → public health."

First, to investigate the relationship between government environmental attention and environmental governance, we establish the following econometric model proposed by Shi et al. (2019).

$$\ln(EI_{it}) = \beta_0 + \beta_1 \ln(WF_{it}) + \beta_2 Z_{it} + YearFE + ProvinceFE + \varepsilon_{it} \quad (2)$$

where EI is the dependent variable and denotes environmental governance investment; WF is the explanatory variable; Z represents the control variable, which includes gross domestic production (GDP) per capita ($PGDP$), value of imports and exports ($Open$), provincial governor's gender ($Gender$), education attainment (Edu), age (Age), and tenure ($Tenure$); and the rest of the variables are defined in the same way as in Model (1).

Second, in 1972, Grossman developed a health production function for the first time, but it has a significant drawback in that it does not take into account macro variables such as environmental factors. Government pro-environmental behavior may exert influences on public mental health and thus physical health (Smyth et al., 2008). Therefore, based on an aggregate-level health production function later revised by Filmer and Pritchett (1999), this paper constructs the following econometric model to explore the impact of government environmental governance investment on public health:

$$\ln(Health_{it}) = \gamma_0 + \gamma_1 \ln(EI_{it}) + \gamma_2 Z_{it} + YearFE + ProvinceFE + \varepsilon_{it} \quad (3)$$

where $Health$ is the dependent variable; EI is the explanatory variable; Z is the control variable, which includes the proportion of urbanization ($Urbanization$), degree of ageing ($Aging$), level of education ($Education$), level of medical advancement ($Medical$); and the rest of the variables are defined in the same way as in Model (1).

2.2 Data and variables

2.2.1 Data

This paper selects 31 provinces in Mainland China as the research setting, with a time span from 2004 to 2017. Government environmental attention (WF) data are based on government work reports sourced from the official websites of China's provincial governments.

Besides, we use a web scraping technique to obtain the characteristic variables of provincial governors from the China Economic Net website and then manually cross-validate the data obtained to ensure data reliability. Other regional variable data come from China's National Bureau of Statistics, Statistical Yearbook, Health Statistics Yearbook, and Environmental Statistics Yearbook.

2.2.2 Measuring government environmental attention

Following Shi et al. (2019), we construct the government environmental attention variable using textual analysis, which is a methodology that incorporates qualitative and quantitative analysis. It was initially utilized in intelligence and informatics but it is now widely used in social sciences as well (Zhang et al., 2021). In this paper, we use the natural language processing (NLP) approach, which is a text mining technique that automatically transforms unstructured texts into structured data and allows researchers to perform quantitative analysis. Through NLP, we can obtain the frequency of environment-related words appearing in government work reports, so as to construct the environmental attention variable. The specifics of the process are as follows.

In step 1, we construct the environmental dictionary. We use Python's Jieba package to automatically split the words of 465 government work reports yielding 20,000 vocabularies. A prototype environmental dictionary is then created by removing entries that are not related to the environment. To maintain objectivity, we enlist the help of professionals from industry and academia to review and filter the preliminary environmental vocabularies, resulting in the final environmental dictionary, which contains 440 entries that are highly relevant to the government's environmental attention.

In step 2, we count relevant words according to the environmental dictionary. Based on the built environmental dictionary, we obtain the frequency of environment-related words in the future plan section of the aforementioned 465 government work reports by python. Then we use the obtained word frequency from each government work report to measure government environmental attention.

2.2.3 Variables

The previous section introduced the measurement of the explanatory variable, government environmental attention (WF). Following Shi et al. (2019), we choose environmental governance

TABLE 1 Variable descriptions.

Variable	Description	Obs	Mean	S.D.	Median	Source
<i>MMR</i>	Maternal mortality rate	434	8.12	4.23	7.19	China health statistics yearbook
<i>PMR</i>	Perinatal mortality rate	434	28.96	37.31	17.72	China Health Statistics Yearbook
<i>EI</i>	Environmental governance investment	434	188.67	186.23	137.70	China Environmental Statistics Yearbook
<i>WF</i>	Word frequency	434	93.95	35.17	92.00	Official websites of provincial governments
<i>Open</i>	International trade/GDP	434	0.30	0.35	0.14	China Statistical Yearbook
<i>PGDP</i>	GDP per capita	434	36,464.37	24,158.45	32,295.50	National Bureau of Statistics of China
<i>Gender^a</i>	Leader's gender	434	0.02	0.13	0.00	Chinese Economic Net
<i>Tenure</i>	Leader's tenure	434	4.43	1.96	4.00	Chinese Economic Net
<i>Edu^b</i>	Leader's education	434	1.85	0.69	2.00	Chinese Economic Net
<i>Age</i>	Leader's age	434	58.09	4.24	59.00	Chinese Economic Net
<i>Urbanization</i>	Urban Population/Total population	434	52.61	15.53	50.94	China Statistical Yearbook
<i>Aging</i>	Number of persons over 65/Total population	434	9.31	1.97	9.11	China Health Statistics Yearbook
<i>Education</i>	Illiterate and semi-literate population over 15 years/Total population	434	8.07	7.13	5.87	National Bureau of Statistics of China
<i>Medical</i>	Number of hospital beds per thousand people	434	4.01	1.35	3.94	China Health Statistics Yearbook

^aGender: Male is 0, Female is 1.

^bEdu: ≤ Year 12 is 0, Bachelor's degree is 1, Master's degree is 2, and Doctoral degree is 3.

investment (*EI*) as a proxy for government environmental governance as the mediating variable, since government environmental governance is primarily reflected through environmental investment expenditures.

We choose pregnant people and perinatal infants as the research setting and use maternal mortality rate (*MMR*) and perinatal mortality rate (*PMR*) to measure public health for the dependent variables (McGuire, 2006). This is because pregnant people and infants have a low cross-regional migration rate and research has confirmed that certain pollutants, especially NO_x and SO_2 , are highly associated with an increased risk of perinatal and maternal mortality (Wang et al., 2019). The *MMR* is the ratio of maternal deaths—those that occur from gestation to 42 days after delivery and are related to pregnancy or pregnancy management causes (excluding accidental deaths)—per 100,000 mothers in a given year. The perinatal mortality rate is the ratio of neonatal deaths—those that occur from 28 weeks of gestation to the 7 days after delivery or with birth weights $\geq 1,000$ g (including fetal deaths and stillbirths)—to the total number of live births.

In addition, we select a set of regional characteristics and governors' personal characteristics as control variables, which is consistent with existing literature. The regional factors are *PGDP* (Tamazian et al., 2009), *Open* (Wang and Chen, 2014; Liu et al., 2017), *Urbanization* (Liu et al., 2003; Li et al., 2016), *Aging* (Bolin et al., 2003; Xu and Chen, 2019), *Education* (Hahn and Truman, 2015) and *Medical* (Kim and Moody, 1992). The personal characteristics of governors are *Gender*, *Edu*, *Age*, and *Tenure* (Shi et al., 2019). The variables are detailed in Table 1.

3 Results

3.1 Descriptive statistics

Figure 1 illustrates the changes in the median word frequency of environment-related vocabularies in the government work reports of the 31 provinces from 2004 to 2017. Overall, government environmental attention is showing an upward trend with fluctuations. Between 2004 and 2008, the frequency of environment-related words in the government work report demonstrates a significant growth trend. The rise reflects the incremental transition of government attention from economic growth to environmental protection as a result of severe environmental degradation caused by extensive economic development in the past (Zhang et al., 2020). Such a transition has intensified China's environmental regulations and governance. During the 5 years from 2004 to 2008, the government promulgated and revised a number of environmental legislations, including the "Solid Waste Environmental Pollution Prevention and Control Law" and the "Renewable Energy Law," demonstrating a solid commitment for legislative solutions to environmental issues. However, the 2008 global financial crisis (GFC) significantly diverted government attention away from the environment and toward economic recovery. As the impact of GFC began to fade, government environmental attention started to rise steadily again. Notably, government environmental attention peaked at 2011 when the 12th Five-Year Plan started and then at 2016 when the 13th Five-Year Plan started.

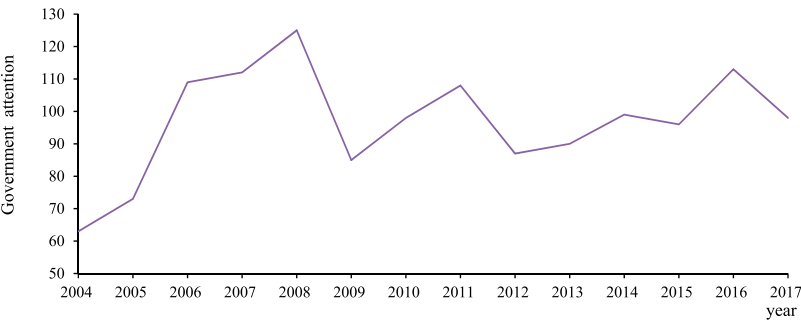


FIGURE 1
Time-series plot of government environmental attention over 2004–2017.

3.2 Baseline regression results

Columns (1) and (2) show the impact of government environmental attention on maternal mortality rate (*MMR*), and Columns (3) and (4) show the impact of government environmental attention on perinatal mortality rate (*PMR*) [Table 2](#). Specifically, Columns (1) and (3) report the regression results controlling for year fixed effects and province fixed effects without adding any control variables. The results indicate that government environmental attention negatively affects maternal mortality rate (*MMR*) as well as perinatal mortality rate (*PMR*) and is statistically significant at the one percent level, suggesting a significant contribution of government environmental attention to public health. In columns (2) and (4), the results indicate that the regression coefficient of government environmental attention (*WF*) is still significantly negative at the one percent level after controlling for regional characteristics as well as governors’ personal characteristics, further confirming the significant and positive effect of government environmental attention on public health. These findings are consistent with the attention-driven policy choice model, which states that when government environmental attention increases, they make the decision to implement corresponding public policies ([Jones, 1994](#)). Therefore, as government environmental attention increases, the government may take actions to address environmental problems, which in turn may affect the level of public health ().

3.3 Mechanism analysis

In this section, we regress Models (2) and (3) to test the mediating effect of government environmental governance investment in government environmental attention and public health. [Table 3](#) presents the regression results.

TABLE 2 Results for baseline regressions.

Variable	ln <i>MMR</i>	ln <i>MMR</i>	ln <i>PMR</i>	ln <i>PMR</i>
	(1)	(2)	(3)	(4)
ln <i>WF</i>	−0.4095*** (0.0877)	−0.1493*** (0.0455)	−0.2556*** (0.0538)	−0.1358*** (0.0319)
ln <i>PGDP</i>		−0.5991*** (0.0665)		−0.3675*** (0.0466)
<i>Open</i>		−0.0425 (0.0715)		−0.0501 (0.0501)
<i>Gender</i>		−0.0954 (0.1533)		0.0730 (0.1074)
<i>Edu</i>		−0.0793** (0.0320)		0.0001 (0.0224)
<i>Age</i>		−0.0105** (0.0048)		−0.0092*** (0.0033)
<i>Tenure</i>		0.0056 (0.0105)		0.0294*** (0.0074)
<i>Urbanization</i>		−0.5523*** (0.1636)		−0.1880 (0.1146)
<i>Aging</i>		−0.9166*** (0.1035)		−0.9499*** (0.0725)
<i>Education</i>		0.2864*** (0.0432)		0.0008 (0.0302)
<i>Medical</i>		0.6209*** (0.0944)		0.1815*** (0.0661)
Constant	4.4896*** (0.4007)	13.4022*** (0.6596)	2.9641*** (0.2456)	9.3632*** (0.4620)
Year FE	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes
Observations	434	434	434	434
R-squared	0.0987	0.7743	0.0817	0.6996

Note: ***, **, and * represent significant at 1, 5, and 10% significance level, respectively; standard errors are provided in parentheses.

TABLE 3 Results for mediation analysis.

Variable	ln EI	ln MMR	ln PMR
	(1)	(2)	(3)
ln WF	0.5335*** (0.1061)		
ln EI		-0.2768*** (0.0206)	-0.1296*** (0.0158)
ln PGDP	1.1868*** (0.0800)		
Open	-0.4167*** (0.1416)		
Gender	-0.2941 (0.3550)		
Edu	0.0080 (0.0745)		
Age	0.0271** (0.0109)		
Tenure	-0.0114 (0.0240)		
Urbanization		-1.3680*** (0.1069)	-0.6341*** (0.0817)
Aging		-0.4242*** (0.1035)	-0.7450*** (0.0791)
Education		0.0785* (0.0418)	-0.0835*** (0.0319)
Medical		0.2342*** (0.0683)	-0.0597 (0.0522)
Constant	-10.9687*** (1.0296)	10.1669*** (0.4232)	6.9625*** (0.3235)
Year FE	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Observations	434	434	434
R-squared	0.4835	0.7947	0.6746

Note: ***, **, and * represent significant at 1, 5, and 10% significance level, respectively; standard errors are provided in parentheses.

Column (1) shows the impact of government environmental attention on government environmental governance investment, while columns (2) and (3) demonstrate the impact of government environmental governance investment on maternal mortality rate (MMR) and perinatal mortality rate (PMR), respectively.

The results in Column (1) reveal a significant positive relationship between ln WF and ln EI after controlling for regional characteristics and governors' personal characteristics. Specifically, for every 1% increase in the frequency of environment-related words (WF), government environmental governance investment (EI) increases by 0.5335%. Consistent with our expectation, this finding shows that an increase in government environmental

attention would result in a significant increase in government environmental governance investment. It implies that the environmental commitments made in the government work reports have been fulfilled, and regional environmental governance has progressed, offering an essential prerequisite and guarantee for regional environmental quality improvement. The results empirically support the attention-driven theory in the psychological nexus between government attention and environmental governance behavior.

Columns (2) and (3) show that the impacts of ln EI on ln MMR and ln PMR are both statistically significant and negative ($p < 0.01$). With every 1% increase in government environmental governance investment (EI), the maternal mortality rate (MMR) and perinatal mortality rate (PMR) decrease by 0.2768% and 0.1296%, respectively. The result suggests that increasing government environmental governance investment will significantly enhance public health.

From the above analysis, we find a significant positive relationship between government environmental attention and environmental governance investment, and between government environmental governance investment and public health. These results support the attention-driven model of policy choice that government environmental attention has been effectively transformed into actions, thus enhancing local environment quality and public health. This finding highlights the critical role of government in environmental governance.

3.4 Robustness checks

We perform our robustness checks by narrowing down the dictionary of government environmental attention to more directly related words and mitigating endogeneity concerns.

3.4.1 Narrowed environmental attention dictionary

To test the robustness of our environmental attention measure, we exclude words that are not directly related to environmental attention and narrow down our environmental dictionary to include more environment-related words. The narrowed dictionary includes 416 words. Following the same procedure, we then use these remaining words to re-construct the government environmental attention variable (ln WF2) and re-estimate the regression models. The results are displayed in Table 4.

Table 4 shows the results for the re-estimated regression models with alternative measure of government environmental attention. The regression results are consistent with our main finding that government environmental attention has a significant and positive impact on public health. Therefore, our main finding is robust to alternative measure of key explanatory variable. The results are reliable and valid.

TABLE 4 Robustness tests for narrowed dictionary.

Variable	ln MMR	ln PMR
	(1)	(2)
ln WF	−0.1385*** (0.0456)	−0.1357*** (0.0319)
Constant	13.3286*** (0.6580)	9.3336*** (0.4601)
Controls	Yes	Yes
Year FE	Yes	Yes
Province FE	Yes	Yes
Observations	434	434
R-squared	0.7735	0.6996

Note: ***, **, and * represent significant at 1, 5, and 10% significance level, respectively; standard errors are provided in parentheses.

TABLE 5 Two-stage instrumental variable regressions.

Variable	ln WF	ln MMR	ln PMR
	(1)	(2)	(3)
Rice	0.1555** (0.0788)		
ln WF		−2.1763*** (0.4443)	−2.9161*** (0.3134)
Constant	4.7285*** (0.7232)	23.0438*** (2.0282)	21.3225*** (1.4305)
Controls	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Observations	406	406	406
R-squared	0.0698	0.7964	0.7319

Note: ***, **, and * represent significant at 1, 5, and 10% significance level, respectively; standard errors are provided in parentheses.

3.4.2 Endogeneity test

To mitigate potential endogeneity problems in the relationship between government environmental attention and public health, this study employs the instrumental variables approach.

An ideal instrumental variable should be strongly correlated with government environmental attention, but should not have a direct effect on public health. Therefore, we run a two-stage least squares (2SLS) regression using the ratio of historical paddy fields to arable land (*Rice*) in each province as an instrumental variable. According to rice theory, regions with a long history of rice cultivation have a stronger collectivist culture compared to regions that grow wheat (Talhelm et al., 2014). Additionally, regions with a stronger collectivist culture are more likely to have a populace with pro-environmental sentiments (Saracevic et al.,

2022), and the local government will pay more attention to environmental issues. Again, paddy field size is unlikely to directly affect public health. We report the regression results in Table 5. Based on the results of the first stage, paddy field size is significantly and positively related to government environmental attention, as we expected. Then we bring the government environmental attention variable (ln WF) estimated in the first stage into the second stage regression and find that the coefficient of ln WF is still significantly negative. This result confirms the positive causal relationship between government environmental attention and public health. Thus, our main finding that government environmental attention has a significant and positive impact on public health is reliable.

3.5 Additional analyses

3.5.1 Regional effect

Due to the significant economic disparities between Eastern China and Central and Western China (Su et al., 2020), there is regional heterogeneity in the allocation of government attention and thus the impact of government environmental attention on public health. We divide the country into Eastern China and Central and Western China according to the standard regional classification of China's National Bureau of Statistics. Eastern China has 13 provinces, including Liaoning, Jilin, Heilongjiang, Beijing, Tianjin, Hebei, Shandong, Shanghai, Jiangsu, Zhejiang, Fujian, Guangdong, and Hainan. Central and Western China has the remaining 18 provinces, including Chongqing, Sichuan, Hubei, Hunan, Anhui, Jiangxi, Shaanxi, Gansu, Ningxia, Shanxi, Henan, Yunnan, Guizhou, Guangxi, Inner Mongolia, Xinjiang, Qinghai, and Tibet. Therefore, to test the regional heterogeneity in the relationship between government environmental attention, government environmental governance investment, and public health, we divide the sample into two groups, Eastern China and Central and Western China, and regress Models (2) and (3), respectively.

Columns (1)–(3) report the regression results for Eastern China (Table 6). The results show no significant causal relationship between ln WF and ln EI, but the impacts of ln EI on ln MMR and ln PMR are both significant and negative. Specifically, although environmental governance investment in Eastern China has improved public health dramatically, government environmental attention has not been significantly transformed into government investment in environmental governance.

Column (4)–(6) display the regression results for Central and Western China. Overall, the results are consistent with the baseline findings. In Central and Western China, there is a significant positive relationship between ln WF and ln EI. Specifically, for every 1% increase in the frequency of

TABLE 6 Results for regional effect.

Variable	Eastern region			Central and western region		
	ln EI	ln MMR	ln PMR	ln EI	ln MMR	ln PMR
	(1)	(2)	(3)	(4)	(5)	(6)
ln WF	0.2087 (0.1587)			0.7883*** (0.1366)		
ln EI		−0.2504*** (0.0279)	−0.1165*** (0.0212)		−0.2888*** (0.0365)	−0.1640*** (0.0254)
Constant	−8.8450*** (1.6598)	10.0666*** (0.7689)	6.1285*** (0.5848)	−11.7120*** (1.2782)	8.2505*** (0.6160)	7.0264*** (0.4283)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	182	182	182	252	252	252
R-squared	0.3498	0.6030	0.5781	0.5649	0.7829	0.7526

Note: ***, **, and * represent significant at 1, 5, and 10% significance level, respectively; standard errors are provided in parentheses.

environment-related words (WF) induces government environmental governance investment (EI) to increase by 0.7883%, which is a greater positive impact compared with that of Eastern China. Increasing investment in environmental governance would also significantly improve public health.

The preceding results demonstrate regional heterogeneity in the relationship between government environmental attention and government environmental governance investment. Further analysis of the government work reports shows that, although the amount of government environmental attention in Eastern China is not significantly different from that in Central and Western China, the priorities are inconsistent. Governments in Eastern China are predominantly concerned with corporate environmental pollution control. Common keywords in local government work reports include “pollution prevention and control,” “energy saving and emission reduction,” and “green production.” Accordingly, in Eastern China, the environmental governance model emphasizes corporate self-governance, which will help increase corporate environmental awareness and encourage green innovation (Bernauer et al., 2007; Li et al., 2019). On the other hand, governments in Central and Western China focus on ecological compensation and protection. The keywords regularly mentioned in local government work reports are “ecological compensation,” “ecological protection,” and “establishment of ecological reserves.” The ecosystem provides public goods and services such as freshwater and purification of air. Therefore, ecological conservation is mostly funded through central and local government environmental investments (Arriagada and Perrings, 2011). Accordingly, in Central and Western China,

government environmental governance investment plays a more significant role. In different regions of China, governments have different priorities to allocate their environmental attention. Such difference is embodied in the government work reports and again supports the attention-driven theory.

3.5.2 Openness effect

There are two opposite views on the environmental consequences of opening up the economy. Some reckon that foreign trades bring environmental benefits to developing countries by upgrading production technologies to save energy and reduce pollution, thereby improving local environmental quality. Others, in contrast, argue that foreign trades have increased the production scale while worsening environmental pollution. Therefore, we divide the 31 provinces of Mainland China into high- and low-openness regions with the cutoff value of median openness (*Open*) and examine the relationship between government environmental attention, environmental governance investment, and public health at different levels of openness.

Table 7 demonstrates openness heterogeneity in the relationship between government environmental attention, government environmental governance investment, and public health. Columns (1)–(3) report the regression results for high-openness regions. The results show that the impact of ln WF on ln EI is not significant ($p > 0.1$) in the high-openness provinces, implying that government environmental attention has no significant impact on government environmental governance investment. However, the results in columns (2) and (3) indicate that government environmental governance investment has significantly improved public health ($p <$

TABLE 7 Results for openness effect.

Variable	High-openness region			Low-openness region		
	ln EI	ln MMR	ln PMR	ln EI	ln MMR	ln PMR
	(1)	(2)	(3)	(4)	(5)	(6)
ln WF	0.2023 (0.1441)			0.8417*** (0.1464)		
ln EI		−0.2892*** (0.0333)	−0.1263*** (0.0263)		−0.2872*** (0.0264)	−0.1630*** (0.0175)
Constant	−7.8811*** (1.4210)	10.7509*** (0.6648)	7.5628*** (0.5239)	−11.6869*** (1.5258)	7.9276*** (0.6104)	5.8192*** (0.4058)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	210	210	210	224	224	224
R-squared	0.4137	0.6313	0.5203	0.5233	0.8568	0.8266

Note: ***, **, and * represent significant at 1, 5, and 10% significance level, respectively; standard errors are provided in parentheses.

0.01). In contrast, the results in columns (4)–(6) reveal that in the low-openness regions, government environmental attention has a significant positive impact on government environmental governance investment ($p < 0.01$), implying that increasing government environmental governance investment would significantly improve public health.

The degree of openness represents the extent to which the region participates in international economic activities and its ability to attract foreign investment (Liargovas and Skandalis, 2012). Openness heterogeneity in the relationship between government environmental attention and public health reflects the effectiveness of openness in China. In high-openness regions, the infrastructure and technology for environmental protection and energy efficiency are well-developed (Bechtel and Tosun, 2009; Managi et al., 2009), while in the low-openness regions, they are still in the early developing stages and require massive government investment (Wu et al., 2019). Therefore, as the attention-driven model of government policy choice suggests, the impact of government environmental attention on environmental governance investment varies across openness levels.

3.5.3 Effect of the 2006 cadre evaluation system reform

On 3 December 2005, China reformed the cadre evaluation system by incorporating environmental performance into the evaluation scheme. Therefore, we choose 2006 as the cut-off point and divide the sample period into two subperiods to explore the impact of the 2006 cadre evaluation system reform on the relationship between government environmental attention, environmental governance investment, and public health.

The results in Column (1) reveal that before 2006, government environmental attention had no substantial effect on government environmental governance investment (Table 8). However, after 2006, as shown in Column (4), government environmental attention has significantly increased environmental governance investment. The results in Columns (3), (5), and (6) are consistent with the baseline regression results, i.e., the impacts of ln EI on ln MMR and ln PMR are all negative and highly significant, suggesting that environmental governance investment has a positive and significant impact on public health.

Taken together, adding environmental performance into the cadre evaluation system has significantly transformed government environmental attention into actions. Before 2006, GDP was the key criterion for cadre evaluation; thus, local officials paid more attention to economic development. However, following the 2006 cadre evaluation system reform that links environmental performance directly to government official promotion, local government planning has shifted significantly from GDP-oriented to green-oriented. Therefore, consistent with the attention-driven theory, government environmental attention has a significant positive relationship with government environmental governance investment since 2006. For every 1% increase in the frequency of environmental-related words in the government work report, government environmental governance investment increases by 0.6488%; and for every 1% increase in government environmental governance investment, maternal mortality rate and perinatal mortality rate fall by 0.2808% and 0.1361%, respectively.

TABLE 8 Results for the effect of the 2006 cadre evaluation system reform.

Variable	Before 2006			After 2006		
	ln EI	ln MMR	ln PMR	ln EI	ln MMR	ln PMR
	(1)	(2)	(3)	(4)	(5)	(6)
ln WF	0.3342 (0.4011)			0.6488*** (0.1165)		
ln EI		−0.1960*** (0.0726)	−0.0231 (0.0341)		−0.2808*** (0.0213)	−0.1361*** (0.0177)
Constant	−13.4871** (5.1722)	10.3340*** (1.2971)	6.4966*** (0.6091)	−12.7298*** (1.3221)	10.1510*** (0.4371)	7.1756*** (0.3627)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	62	62	62	372	372	372
R-squared	0.3575	0.7343	0.7451	0.4488	0.7918	0.6420

Note: ***, **, and * represent significant at 1, 5, and 10% significance level, respectively; standard errors are provided in parentheses.

4 Discussion and conclusion

The pollutant emissions of enterprises not only harm the environment, but they also pose a serious threat to public health, necessitating urgent government intervention. Therefore, this study examines the impact of government environmental attention on public health based on government attention-driven policy choice theory and discusses the mediating role of government environmental governance investment. Our findings suggest that (1) government environmental attention has a significant and positive impact on public health, with each 1% increase in government environmental attention decreasing the maternal mortality rate by 0.1493% and perinatal mortality rate by 0.1358%; (2) environmental governance investment plays a mediating role in the relationship between government environmental attention and public health; (3) the results remain robust after replacing the explanatory variables and mitigating endogeneity concerns; (4) government environmental attention has a significant and positive effect on environmental governance investment in Central and Western China, in low openness regions, and after China incorporated environmental performance in the cadre evaluation system in 2006.

Based on our findings, we propose the following three suggestions for corporate sustainable development. First, firms should engage in environmental governance and take responsibility for environmental protection. The government and the general public have been increasingly demanding environmental protection since the implementation of the “carbon neutrality” and “carbon peak” targets. As key participants and stakeholders, it is critical for firms to

participate in environmental governance. Firms should make production decisions from a green perspective, invest more in green research and development, continuously enhance productivity, and push for production transformation and technological innovation to help achieve the “carbon neutrality” goal.

Second, a green development policy framework, as well as a corporate environmental information disclosure system, should be developed. In the context of China’s economy, the government should implement tax policies that are conducive to energy conservation, environmental protection, and comprehensive resource utilization, improve environmental protection tax laws, and minimize the negative impacts of environmental regulations on business operations. Simultaneously, the government should standardize corporate environmental information disclosure processes, and impose administrative fines on firms that fail to disclose environmental information on time or in a complete and accurate manner, so as to curb corporate “greenwashing.”

Third, there should be synergistic governance of environmental issues between the government and businesses to promote corporate sustainability. The government, in particular, should pay more attention to corporate environmental issues, adjust pollutant emissions costs through regulatory advice, and encourage firms to produce in an environmentally friendly manner. Simultaneously, it should establish a corporate environmental social responsibility incentive mechanism, differentiate the incentives, and provide greater support and benefits to firms that perform better in terms of environmental responsibility to ensure their green coordinated development.

Finally, as in almost every study, there are limitations in this study as well. First, the government environmental attention variable in this paper is derived from the textual analysis of local annual government work reports, which is one of the few feasible options available. However, because objective indications of government behaviors are difficult to measure, verifying the validity of the textual analysis is challenging. Second, this study looks at the environmental attention of provincial governments and future studies can zoom into the city- and firm-level investigations. Third, alternative mediating mechanisms can be further explored.

Data availability statement

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

Author contributions

JT: methodology, validation, supervision. SZ: methodology, formal analysis, software, writing—review and editing. XW: data curation, writing—original draft preparation. SZ: software, formal analysis, writing—original draft preparation. MZ:

software, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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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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How does D&O insurance affect corporate environmental investment?

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Directors' and officers' liability insurance (D&O insurance), an important tool for diversifying and transferring risks of managers, plays a crucial role in corporate investment decisions, including corporate environmental investment decisions. However, the relationship between D&O insurance and corporate environmental investment remains unknown. Using a sample of Chinese listed firms, this study examines whether and how D&O insurance affects corporate environmental investment from 2008 to 2019. We find that D&O insurance is negatively associated with corporate environmental investment. This result is consistent with the results of a series of robustness tests. Further analyses show that D&O insurance impedes corporate environmental investment by driving executives to seek private benefits, especially monetary benefits. Moreover, the negative effect of D&O insurance on corporate environmental investment is more pronounced in low-polluting and highly competitive industries. However, this negative relationship is mitigated by political connections. The findings contribute to the literature by providing empirical evidence of the involvement of D&O insurance in influencing corporate environmental investment decisions.

KEYWORDS

D&O insurance, corporate environmental investment, private benefits, monetary benefits, political connections

1 Introduction

In recent years, with the rapid economic development in China, environmental problems have become more prominent (Tang et al., 2013; Yan and Xu, 2020). In 2002, the United Nations released the China Human Development Report, which pointed out that environmental pollution in China caused an annual GDP loss of approximately 3.5%–8%, and that more than 80% of the environmental pollution in China arises from the corporate sector (Shen et al., 2012). Owing to the deterioration of the ecological environment, the Chinese government increasingly values environmental protection, actively participates in green practices, and proposes and implements a series of goals and

Abbreviations: D&O insurance, directors' and officers' liability insurance.

policies for green production and low-carbon emissions. In practice, according to the statistics of [Tian et al. \(2022\)](#), the Chinese government has invested 40.51 billion USD in the energy sector, of which 67.66% has been invested in green and clean energy. Regarding policies, in 2008, the guidelines for the disclosure of environmental information for companies listed on the Shanghai Stock Exchange required heavily polluting industries to publish information on their environmental performance. In 2015, the Chinese government implemented strict corporate environmental regulations, imposing fines and even imprisonment on companies that violated the law. In September 2020, President Xi Jinping proposed the climate action targets of “2030 Carbon Peak, 2060 Carbon Neutral” at the United Nations General Assembly. He also proposed the 14th Five-Year Plan for National Economic and Social Development of the People’s Republic of China and the Outline of Vision 2035, both of which included accelerating green and low-carbon development as a crucial objective and task. This further establishes the importance of green development in the new era of China’s development.

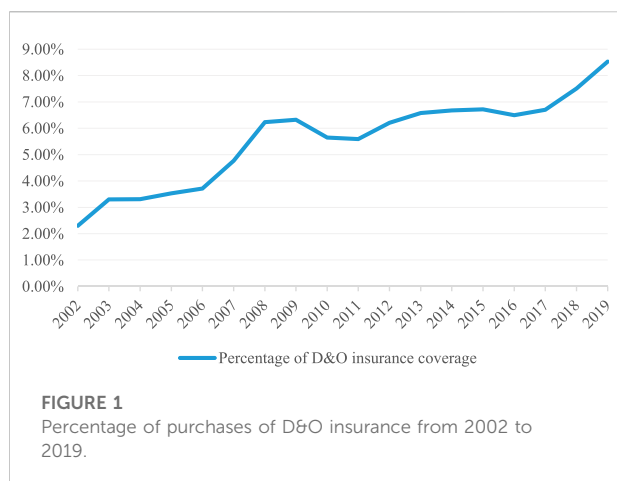
Despite the aforementioned regulations and government initiatives established for corporate environmental responsibility, China still faces environmental governance problems. For example, environmental investment is dominated by the government, and the level of corporate environmental investment is relatively low ([Claessens et al., 2000](#)), and this type of investment is mostly motivated by legal requirements or gaining a competitive advantage ([Maggioni and Santangelo, 2017](#)). However, according to the “who pollutes, who controls; who exploits, who protects” principle established by China’s New Environmental Protection Law and the “polluter pays” principle advocated by the Organization for Economic Co-operation and Development (OECD), enterprises, which are the main consumers of natural resources and the main producers of environmental pollution, should bear the primary responsibility of environmental protection and increasing green investment ([Tang et al., 2013](#)).

D&O insurance is a type of liability insurance purchased by a company to protect all directors and managers against certain losses from lawsuits arising from poor management decisions and other wrongful acts in that capacity ([Yuan et al., 2016](#)). Existing studies have widely investigated the economic consequences of D&O insurance. However, two opposing views remain. One view is that D&O insurance can provide protection for directors and officers from the threat of litigation and reduce their concerns about the performance of their duties, thereby reducing agency costs ([Hoyt and Khang, 2000](#)), encouraging firm innovation ([Wang et al., 2020](#)), increasing firm value ([Hwang and Kim, 2018](#)), and conveying information about the corporate governance of the insured firm ([Chen, 2016](#)). Another view is that D&O insurance weakens the disciplinary effect of shareholder lawsuits, which

could drive firms to make economic overinvestments ([Li and Liao, 2014](#)) and inefficient mergers and acquisitions ([Lin et al., 2011](#)) and lead to aggressive earning management ([Boyer and Tennyson, 2015](#)).

As an important tool to diversify and transfer risks of managers, D&O insurance plays a crucial role in corporate investment decisions, including corporate environmental investment decisions. The purpose of the study was to examine whether and how D&O insurance affects corporate environmental investment. In theory, D&O insurance also has a two-fold impact on corporate environmental investment. On the one hand, D&O insurance can increase the incentive for directors and officers to act in the interests of their stakeholders, thus promoting corporate environmental investment; on the other hand, D&O insurance can reinforce moral hazard and induce executives to seek private benefits, thereby impeding corporate environmental investment. Consequently, what is the effect of D&O insurance on corporate environmental investment? What are the influencing mechanisms through which D&O insurance affects corporate environmental investment? Does the effect vary among different industries? Whether the effect is influenced by the moderating effect of political connections? To answer the aforementioned questions, we conduct our research based on the data of A-share listed companies in China’s Shanghai and Shenzhen stock exchanges from 2008 to 2019. We find that D&O insurance is negatively associated with the corporate environmental investment. The intermediary mechanism suggests that D&O insurance impedes corporate environmental investment by prompting executives to seek monetary private benefits. Further analyses show that the negative impact of D&O insurance on corporate environmental investment is more pronounced in low-polluting and highly competitive industries, but the negative relationship is mitigated by political connections.

This study makes several contributions to the literature. (1) We expand the literature on corporate environmental investment from the perspective of D&O insurance and executives seeking private benefits. To the best of our knowledge, this study is the first to examine the impact of D&O insurance on corporate environmental investment, by identifying new factors affecting the investment, thus enriching the literature on this type of investment. (2) We also contribute to the literature on the environmental and economic consequences of D&O insurance. Although the economic consequences of D&O insurance have been widely examined, there is no unanimous conclusion on the role of D&O insurance in corporate governance, and it is impossible to understand the environmental consequences of D&O insurance. This study sheds light on the effectiveness of D&O insurance on corporate governance and further enriches the literature on its consequences. (3) We also show that government connections have a significant impact on the relationship between D&O insurance and corporate environmental investment, thereby



providing important empirical evidence for government regulators to formulate environmental policies.

The remainder of this study is organized as follows: [Section 2](#) provides the background of D&O insurance and proposes hypotheses. [Section 3](#) refers to the research design. [Section 4](#) represents empirical results. [Section 5](#) provides the intermediary mechanism tests, heterogeneity analyses, and moderating effect tests. Finally, [Section 6](#) gives conclusions and policy suggestions.

2 Background and hypotheses development

2.1 Background

In the early 1930s, the collapse of the U.S. stock market evoked strong demand from investors for a better regulatory system for the security market. With the establishment of the U.S. Securities and Exchange Commission and the sanctioning of the Securities Act of 1933 and the Securities Exchange Act of 1934, the business risks borne by directors and officers of US listed companies increased abruptly. As a result, Lloyd's of London introduced D&O insurance in 1934. Subsequently, D&O insurance gradually gained popularity in the security industry and became an important business for insurance companies in developed countries and regions. The percentage of D&O insurance coverage exceeds 70% ([Zou et al., 2008](#); [Yuan et al., 2016](#)).

D&O insurance was introduced relatively late in China. In 2001, China first formulated regulations related to D&O insurance, namely, the Guidance on the Establishment of Independent Directors in Listed Companies, stating that listed companies may establish a D&O insurance system to reduce the risks incurred by directors and officers in the normal performance of their duties. In 2002, the Code of Governance for Listed Companies mentioned that listed companies could

purchase D&O insurance for directors if it was approved in the shareholders' meeting. In the same year, Ping An Insurance and the American Chubb Company jointly provided an insurance policy for Wang Shi, Chairman of Vanke, and this was a prelude to D&O insurance in China.

[Figure 1](#) depicts the number of Chinese listed firms that purchased D&O insurance divided by the total number of listed firms from 2002 to 2019. As shown in [Figure 1](#), the percentage of D&O insurance coverage in China increased from 2.30% in 2002 to 8.53% in 2019. Although the percentage of D&O insurance in China has been rising annually, it is still relatively low. However, with the improvement of the legal system of the capital market and the enhancement of risk awareness of listed companies and investors, the role of D&O insurance has become increasingly prominent, and an increasing number of listed companies have realized the importance of D&O insurance and acquired it. Furthermore, there is still scope for the development of D&O insurance in China, and it is important to study the consequences of D&O insurance.

2.2 Hypothesis development

Environmental investment refers to a range of practices by companies aimed at reducing the direct or indirect environmental impact of organizational processes and products or services, including environmental remediation costs, pollution prevention costs, R&D investment costs to address environmental challenges or environmental product development, recovery costs, and costs to implement environmental management systems ([Orsato, 2006](#); [Bhuiyan et al., 2021](#)).

Prior studies have examined the determinants of environmental investment, including environmental regulation ([Maxwell and Decker, 2006](#); [Chang et al., 2021](#)), political connection ([Yan and Xu, 2020](#)), financial constraints ([Zhang et al., 2019](#)), the controlling shareholder–manager collusion ([Li et al., 2019](#)), managerial strategy ([Costa-Campi et al., 2017](#)), characteristics of CEOs ([Li et al., 2016](#); [Yang et al., 2019](#)), independent directors, especially women directors ([Bhuiyan et al., 2021](#); [Atif et al., 2020](#)), consumers' who are environmentally conscious ([Liu and Wu, 2009](#)), and works councils ([Askildsen et al., 2006](#)). However, the relationship between D&O insurance and corporate environmental investment remains unknown.

Theoretically, D&O insurance may have two effects on corporate environmental investment. On the one hand, D&O insurance may impede corporate environmental investment. The agency theory suggests that shareholders, as principals, are owners of corporate resources, and managers, as agents, are users and controllers of corporate resources. When the interests of managers conflict with those of shareholders and this is coupled with information asymmetry, managers have an

incentive to act according to their interests that is difficult for shareholders to detect, thereby leading to principal-agent problems. However, the existence of D&O insurance may exacerbate these issues. D&O insurance enables the insured to shift liability to the insurance company for damages arising from negligence or misconduct in the performance of their duties, which can easily make the insured ignore the cost of their liability for damage. This not only weakens the disciplinary effect of shareholder lawsuits but also reduces the cost of rent-seeking for executives, resulting in managers being more likely to engage in economic behaviors that maximize their utility but against the best interests of shareholders and stakeholders (Lin et al., 2011; Chen et al., 2016). Studies have provided evidence that D&O insurance leads to moral hazards from the perspectives of overinvestment, corporate mergers and acquisitions, and surplus management. For example, Chan et al. (2019) showed that D&O could easily become an “umbrella” for the self-interested behavior of executives because the risk-averse effect reduces the rent-seeking cost of executives, thereby increasing the eagerness of executives to economically over-invest. Based on a study of firms in Taiwan, Li and Liao, (2014) confirmed that D&O insurance coverage is positively associated with economic overinvestment, indicating that D&O insurance reduces corporate investment efficiency. Moreover, firms with higher levels of D&O insurance coverage are more likely to make aggressive merger and acquisition (M&A) decisions; however, these are accompanied by higher acquisition premiums, lower synergies, and lower shareholder returns (Lin et al., 2011). From the perspective of earning management, Boyer and Tennyson, (2015) and Chung and Wynn, (2008) pointed out that D&O insurance is associated with more aggressive earning management and less conservative earnings. Therefore, it may not be a wise investment for a company to purchase D&O insurance; nonetheless, it may still be of interest to company executives (Griffith, 2006). As executives use company funds to purchase enterprise-level D&O insurance, they protect their compensation and private benefits with a larger but infrequently expected loss, which is a classic representation of agency costs.

As a special form of non-economic investment, corporate environmental investment pursues comprehensive benefits, including economic, environmental, and social benefits; however, due to the diversified target requirements, long investment cycles, and low return on investment, it results in relatively low economic benefits (Gray and Shadbegian, 1998; Fisher-Vanden and Thorburn, 2011; Bhuiyan et al., 2021). Not only is it difficult for corporate environmental investment to generate direct economic inflows, but also it requires the companies to continuously spend large amounts of money on environmental facilities and environmental technology innovation (Orsato, 2006). As managers and firms seek to maximize the short-term economic benefits, they prefer to invest their limited resources in low-risk, high-return projects (Guariglia and Liu, 2014), rather than in less economically

beneficial environmental projects; therefore, they are not willing to pursue environmental management and investment. Moreover, investing limited resources in environmental governance can constrain or crowd out the investment of firms in other economic and productive projects, which is contrary to the profit maximization goal of firms (Gray and Shadbegian, 1998). Particularly, in the Chinese capital market, the compensation evaluation system for executives of Chinese firms focuses on economic performance and does not increase executive compensation because of improved environmental and social performance resulting from corporate environmental investment. Accordingly, we predict that with the risk-sheltering and risk-transfer effects of D&O insurance, self-interested executives will actively seek private benefits associated with economic benefits rather than making decisions to allocate funds to environmental investments that have lower economic benefits or that even crowd out other economic projects.

In summary, based on the aforementioned analysis, the following hypothesis is proposed:

H1a. D&O insurance is negatively associated with corporate environmental investment.

In contrast, D&O insurance may promote corporate environmental investment. D&O insurance increases the level of risk-taking for firms and executives by reducing their worries about incurring losses to the firm due to unintentional misconduct in the performance of their duties, thus helping managers make bold decisions that are beneficial to corporate governance, as well as the interests of shareholders and stakeholders (O'Sullivan, 1997; Jensen, 1993). This includes the decision to increase corporate investment in environmental protection because this may become part of the future core competencies of the company and increase corporate value. With the introduction of various environmental protection policies in China, consumers are becoming aware of the importance of protecting the environment. Therefore, the environmental investment of a company generates reputational benefits and stimulates consumer demand for environmental products (Liu and Wu, 2009), especially in a stable state, a high level of environmental investment also leads to a higher output (Liu and Wu, 2009). The company might then profit from these environmental investments and eventually turn them into core competencies (Orsato, 2006) and increase the company's value. Corporate environmental investment can also be an uncertain, long-term, and trial-and-error process. However, D&O insurance increases the level of risk-taking and the tolerance of managers to failure (Wang et al., 2020), which encourages firms to continue investing in the environment.

In addition, by purchasing D&O insurance, the firm introduces an insurance company as an external monitor that restrains the opportunistic behavior of managers through multiple layers of supervision, thus contributing to a corporate environmental investment increase. Before underwriting, the insurer conducts a comprehensive risk

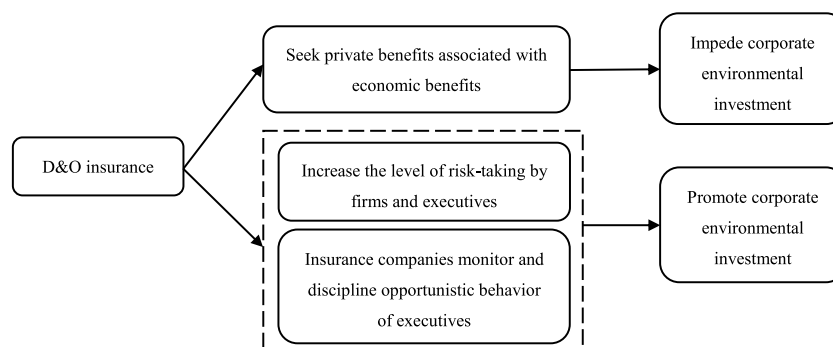


FIGURE 2
Research framework and hypothetical relationships.

assessment of the listed firm and the insured (directors and officers), including the financial situation and the risk management status, on which the rates charged are based (Boyer and Stern, 2014); in particular, the insurer will set strict insurance terms for high litigation risk companies. All of these are conducive to restraining the short-sighted behavior of firms, improving the efficiency of corporate governance, and increasing corporate environmental investment. During underwriting, the insurance company continuously evaluates the level of corporate governance and the project risks. If they find an increased risk of compensation, they will propose a modification plan and urge the firm to implement it, or even produce a warning effect by raising premiums (Li and Xu, 2020), all of which can improve the compensation structure of directors and the ownership structure of executives (O'Sullivan, 1997), and optimize the corporate governance mechanisms. Even in the event of a lawsuit, the insurance company conducts an in-depth investigation and pays for the liability of directors and officers for any negligent acts in performing their duties. To avoid large compensation for environmental liability, insurance companies, which have become corporate stakeholders, also have an incentive to monitor corporate compliance with environmental regulations and increase their investment in environmental protection and pollution reduction (Figure 2).

In summary, based on the aforementioned analysis, the following hypothesis is proposed:

H1b. D&O insurance is positively associated with corporate environmental investment.

3 Research design

3.1 Sample

Since the Guidelines on Disclosure of Environmental Information for Companies Listed on the Shanghai Stock

Exchange were issued in 2008, the environmental investment data began in 2008. Accordingly, our initial sample includes Chinese A-share listed firms in the Shanghai and Shenzhen stock exchanges for the period 2008–2019. We collect our data from several resources. First, data about D&O insurance are from the Chinese Research Data Services (CNRDS) Platform. Second, corporate environmental investment and other financial data were gathered from the China Stock Market & Accounting Research (CSMAR) Database. To enable reasonable precision, all missing environmental investment observations were deleted, and we exclude firms with special treatment, firms that belong to financial industries, and firms with missing values. Limited by corporate environmental investment data, the total number of our final sample is 1,008 for 521 listed firms from 2008 to 2019. All the continuous variables are winsorized at the 1st and 99th percentiles.

3.2 Variables

3.2.1 Dependent variable: corporate environmental investment

Drawing on Li et al. (2019) and Bhuiyan et al. (2021), we use the natural logarithm of the amount of annual environmental investment to measure corporate environmental investment (EI), which is a common way to measure corporate green investment.

3.2.2 Independent variable: directors' and officers' insurance

Following previous studies (Lin et al., 2011; Wang et al., 2020), we adopt a dummy variable to measure D&O insurance (DO), which equals 1 if a firm purchases D&O insurance in a given year, and 0 otherwise.

3.2.3 Control variable

Referring to previous studies (Li and Liao, 2014; Li et al., 2019), we control several factors that could influence a firm's

TABLE 1 Descriptive statistics.

Variable	N	Mean	SD	Min	Median	Max
EI	1008	16.942	2.312	10.477	17.109	22.784
DO	1008	0.108	0.311	0.000	0.000	1.000
Size	1008	22.879	1.443	20.272	22.755	27.040
Lev	1008	0.457	0.200	0.073	0.455	0.919
Roa	1008	0.044	0.053	−0.130	0.038	0.202
Cfo	1008	0.060	0.063	−0.114	0.057	0.238
Growth	1008	0.161	0.269	−0.227	0.092	1.484
Board	1008	2.169	0.197	1.609	2.197	2.708
Indep	1008	0.375	0.057	0.333	0.364	0.600
Top1	1008	37.431	15.785	7.820	36.035	79.960
Msh	1008	0.043	0.105	0.000	0.000	0.542
Age	1008	2.819	0.306	1.946	2.833	3.367

environmental investment activities as follows: firm size (Size), leverage ratio (Lev), return on assets (Roa), cash flow (Cfo), growth capacity (Growth), board size (Board), the proportion of independent directors (Indep), equity concentration (Top1), management shareholding (Msh), and firm age (Age). Furthermore, we control industry (Industry) and year (Year) effects. The definition of the aforementioned variables is presented in [Appendix A](#).

3.3 Empirical model

We employ the following regression using an ordinary least squares (OLS) model with a pooled sample to capture the effect of D&O insurance on environmental investment:

$$EI_{i,t+1} = \alpha_0 + \alpha_1 DO_{i,t} + \sum_j \alpha_j Control_{j,i,t} + Industry_i + Year_i + \epsilon_{i,t}, \quad (1)$$

where i , t , and j refer to firm, year, and control variables, respectively. ϵ_{it} denotes the disturbance. To reflect the long-term nature of environmental investment and alleviate the possible endogeneity issue, we use a one-year lead period to match environmental investment with D&O insurance. Robust standard errors are used in model estimates to eliminate heteroscedasticity.

4 Empirical results

4.1 Descriptive statistics

The descriptive statistics of the main variables in terms of mean value and standard deviation, as well as the minimum and maximum values, are reported in [Table 1](#). The mean value of EI is

TABLE 2 Baseline results.

Variable	EI _{i,t+1} (1)	EI _{i,t+1} (2)
DO		−0.4012** (−2.0516)
Size	0.8831*** (16.0722)	0.9162*** (16.3577)
Lev	0.8642** (2.1902)	0.8079** (2.0471)
Roa	−0.1102 (−0.0771)	−0.0019 (−0.0013)
Cfo	2.4784** (2.5289)	2.3835** (2.4460)
Growth	−0.1407 (−0.5542)	−0.1321 (−0.5170)
Board	0.5885* (1.7491)	0.6323* (1.8833)
Indep	−0.7686 (−0.6213)	−0.6864 (−0.5592)
Top1	0.0077** (2.0410)	0.0080** (2.1363)
Msh	−1.4820** (−2.2806)	−1.4666** (−2.2513)
Age	−0.0255 (−0.1124)	0.0245 (0.1083)
Constant	−5.7052*** (−3.3402)	−6.5485*** (−3.8418)
Industry	Yes	Yes
Year	Yes	Yes
Adj. R ²	0.4608	0.4627
N	1008	1008

Note: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. T-statistics are reported in parentheses and are based on robust standard errors.

16.942, which is similar to the results of [Li et al. \(2019\)](#). The mean value of DO is 0.108, suggesting that 10.8% of firm-year observations are covered with D&O insurance in our sample.

In addition, we calculate the variance inflation factors (VIFs) to evaluate whether multicollinearity exists among the variables. The results in [Appendix B](#) show that the VIF from 1.11 to 2.01, which is substantially lower than the critical value of 10 for multiple regression models ([Griffith and Harvey, 2001](#)), implying that there is no serious problem of multicollinearity in this study.

4.2 Results and analysis

[Table 2](#) reports the results of model 1. In column (1), we only incorporate control variables. Column (1) shows that the coefficients of the control variables are generally consistent with previous findings in the literature. Column (2) shows

TABLE 3 Robustness tests.

Variable	PSM	First stage	Second stage	FE	Tobit	Alternative EI
	EI _{i,t+1}	DO	EI _{i,t+1}	EI _{i,t+1}	EI _{i,t+1}	EI _{a_{i,t+1}}
	(1)	(2)	(3)	(4)	(5)	(6)
DO	−0.7346*** (−2.8299)		−3.3836*** (−3.7259)	−0.8565** (−1.9747)	−0.4012** (−2.0903)	−0.0040* (−1.8983)
IV		0.0037*** (6.5189)				
Constant	−8.0700* (−1.6799)	−1.7572*** (−3.8518)	−12.8174*** (−4.8266)	−0.4420 (−0.0761)	−6.5485*** (−3.9144)	0.0342* (1.8331)
Control	Yes	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	No	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Firm	No	No	No	Yes	No	No
Adj. R ²	0.5762	0.2181	0.3292	0.1160	0.1459	0.2454
N	164	1008	1008	1008	1008	1008

Note: (1) ***, **, and * indicate statistical significance at the 1%, 5% and 10% levels, respectively. T-statistics are reported in parentheses and are based on robust standard errors. (2) Kleibergen–Paap rk LM statistic of the IV-2SLS regression approach is 42.194, and the corresponding *p*-value is 0.0000, indicating that it passed the under-identification test. Kleibergen–Paap rk Wald F statistic is 42.496, and the corresponding critical value at the 10% level of the Stock–Yogo test is 16.38, indicating that it passed the weak identification test.

that the regression coefficient of DO is negative and significant at the 5% level, providing strong support for our [Hypothesis 1a](#), that is, D&O insurance could inhibit corporate environmental investment. The result suggests that D&O insurance provides risk hedging and shelter for corporate executives to engage in behaviors that benefit their personal interests and reduce green investments.

4.3 Robustness tests

4.3.1 Propensity score matching approach

We use the propensity score matching approach to address potential endogeneity. Depending on whether the firm has D&O insurance or not, the treatment variable is considered to be one or zero, respectively. We employ a logit model to generate the propensity score of a firm with D&O insurance using the same control variables in Model 1 and match each observation for a firm with D&O insurance to a control firm with the closest propensity score to that of the analyzed firm. Finally, we obtained 164 firm-year observations. The result in column (1) of [Table 3](#) indicates that the coefficient of DO is significantly negative at the 1% level, which supports our previous conclusions.

To ensure the reliability of the matching, we adopt a balance test, and the results are presented in [Appendix C](#). The standard deviation (% bias) after matching significantly decreases to less than 20%. In addition, no significant difference in the mean of the characteristic variables was observed after matching, according to the statistical analysis using the *t*-test, indicating that the matching effect is effective.

4.3.2 Instrumental variable approach

We further employ the IV-2SLS regression approach to solve potential endogeneity problems. Drawing on [Zhou et al. \(2022\)](#), we use the number of insurance companies where the listed company is located as an instrumental variable. We expect that the higher the number of insurance companies, the more active the insurance market is likely to be, and therefore firms are more likely to cover D&O insurance, but no studies are showing that the number of insurance companies will directly affect corporate environmental investment. Columns (2) and (3) in [Table 3](#) report the results of the 2SLS approach. It suggests that the regression coefficient of DO remains negative and statistically significant at the 1% level. Our results are robust when controlling for the endogeneity issue.

4.3.3 Other robustness tests

To ensure the robustness of our results, we also implement the following robustness tests: first, to address the omitted variable problem, we re-examine the model with fixed effects (FE). The result in column (4) of [Table 3](#) suggests that the baseline regression is robust. Second, we replace the regression model with the Tobit model. Considering that the dependent variable contains some zero values, we replace the baseline OLS model with the Tobit model and re-examine our result. As seen in column (5) in [Table 3](#), the conclusions are consistent with the previous. Last, we substitute the dependent variable. We use the alternative proxy EI_{a_{i,t+1}} measured as the amount of corporate environmental investment divided by the firm's

sales revenue. The result in column (6) in Table 3 remains unaltered.

5 Additional analyses

5.1 Intermediary mechanism tests

In the section on hypothesis development, we suggest that D&O insurance, which shifts the risk of litigation and liability that the insured may face to the insurer, tends to exacerbate principal–agent problems. This causes self-interested executives to actively seek private benefits associated with economic benefits rather than making decisions to allocate funds to environmental investments that are less economically efficient or that even crowd out other economic projects. Thus, we predict that D&O insurance may reduce corporate environmental investments by increasing the private benefits of executives. However, in this section, we further explore the intermediary role of these benefits in the relationship between D&O insurance and environmental investment.

Based on previous studies, we classify the private benefits of executives into monetary and non-monetary benefits. First, according to Firth et al. (2006) and Core et al. (2008), the monetary private benefits of executives refer to abnormal compensation (Abpay), which is measured by the difference between the actual compensation and the expected compensation that is determined by economic factors. The expected compensation is estimated using Model 2:

$$\begin{aligned} \ln pay_{i,t} = & \beta_0 + \beta_1 Size_{i,t} + \beta_2 Roa_{i,t} + \beta_3 Roa_{i,t-1} + \beta_4 Areawage_{i,t} \\ & + \beta_5 Central_{i,t} + \beta_6 West_{i,t} + Industry_t + Year_i + \epsilon_{i,t}, \end{aligned} \quad (2)$$

where $\ln pay$ denotes the natural logarithm of the total compensation of the top three highest paying executives. $Size$ and Roa are consistent with the definition of previous variables. $Areawage$ is the average level of urban employees at the location of the company. $Central$ and $West$ are dummy variables indicating that the listed companies are in the central and western regions, respectively.

Second, according to Luo et al. (2011), the non-monetary private benefits of executives refer to abnormal on-the-job spending (Abperk), which is calculated by the difference between the actual on-the-job spending and the expected on-the-job spending that is determined by economic factors. The expected on-the-job spending is estimated using model 3:

$$\begin{aligned} Perks_{i,t} / Asset_{i,t-1} = & \gamma_0 + \gamma_1 1 / Asset_{i,t-1} + \gamma_2 \Delta Sale_{i,t} / Asset_{i,t-1} \\ & + \gamma_3 PPE_{i,t} / Asset_{i,t-1} \\ & + \gamma_4 Inventory_{i,t} / Asset_{i,t-1} \\ & + \gamma_5 Lnemployee_{i,t} + Industry_t + Year_i \\ & + \epsilon_{i,t}, \end{aligned} \quad (3)$$

where $Perks$ indicates the executive on-the-job spending. $Asset$ is the total assets. $\Delta Sale$ represents the change in primary business revenue in period t . PPE is net fixed assets. $Inventory$ is net inventory for the period t . $Lnemployee$ is the natural logarithm of the total number of employees in the company.

Then, drawing on the intermediary effect model proposed by Baron and Kenny, (1986), we further construct the following models:

$$\begin{aligned} Mediate_{i,t} = & \delta_0 + \delta_1 DO_{i,t} + \sum_j \delta_j Control_{j,i,t} + Industry_t \\ & + Year_i + \epsilon_{i,t}, \end{aligned} \quad (4)$$

$$\begin{aligned} EI_{i,t+1} = & \mu_0 + \mu_1 DO_{i,t} + \mu_2 Mediate_{i,t} + \sum_j \mu_j Control_{j,i,t} \\ & + Industry_t + Year_i + \epsilon_{i,t}, \end{aligned} \quad (5)$$

where i , t , and j represent the firm, year, and control variables, respectively. $Mediate$ refer to $Abpay$ and $Abperk$. DO , EI , and $Control$ are consistent with the definition of variables in the benchmark regression mentioned previously. Robust standard errors are used in model estimates to eliminate heteroscedasticity.

The results of intermediary mechanism tests are reported in Table 4. Columns (1) and (2) show that DO is significantly positively correlated with $Mediate$ ($Mediate = Abpay$) and $Mediate$ ($Mediate = Abpay$) is also significantly negatively associated with $EI_{i,t+1}$, indicating that D&O insurance inhibits corporate environmental investment by increasing monetary private benefits of executives. In addition, the coefficient of DO in column (2) is not significant, suggesting that monetary private benefits play a fully mediating effect in the relationship between D&O insurance and environmental investment. The results in column (3) show that the coefficient of DO is also not significant, indicating that non-monetary private benefits do not play an intermediary role in the process of D&O insurance influencing corporate environmental investment. In summary, our findings of the intermediary mechanism tests show that D&O insurance inhibits corporate environmental investment by driving executives to seek monetary private benefits, whereas non-monetary private benefits play no role.

5.2 Heterogeneity analyses

Table 5 further explores the heterogeneity impact of D&O insurance on corporate environmental investment in different industries. Due to the significant differences in the degree of environmental pollution caused by different industries, corporate environmental investment will be affected by the attributes of polluting industries to a certain extent. Compared with low-polluting industries, high-polluting industries have long been subjected to strict environmental regulations and wide social concerns due to serious environmental pollution problems. Therefore, these industries started with environmental

TABLE 4 Intermediary mechanism tests.

Variable	Monetary private benefit		Non-monetary private benefit	
	Mediate = Abpay		Mediate = Abperk	
	Mediate	EI _{i,t+1}	Mediate	EI _{i,t+1}
	(1)	(2)	(3)	(4)
DO	0.3874*** (5.2813)	−0.2605 (−1.3487)	0.0004 (0.2160)	−0.3812* (−1.8485)
Mediate		−0.2111** (−2.0288)		−4.8823* (−1.7939)
Constant	0.8464 (1.4348)	−5.0650*** (−2.7859)	0.0200 (1.0406)	−6.3210*** (−3.5833)
Control	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Adj. R ²	0.0727	0.4710	0.0431	0.4528
N	939	939	930	930

Note: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. T-statistics are reported in parentheses and are based on robust standard errors.

TABLE 5 Heterogeneity analyses.

Variable	High-polluting	Low-polluting	Low-competitive	High-competitive
	EI _{i,t+1}	EI _{i,t+1}	EI _{i,t+1}	EI _{i,t+1}
	(1)	(2)	(3)	(4)
DO	−0.3019 (−1.4246)	−1.0136** (−2.0035)	−0.0848 (−0.2801)	−0.7290*** (−2.9974)
Constant	−5.7553*** (−3.6016)	−7.7459 (−1.0822)	−7.3878*** (−3.0412)	−5.7337*** (−2.9265)
Control	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Adj. R ²	0.4630	0.4354	0.4487	0.4906
N	893	115	506	502
Empirical <i>p</i> -value	0.020**		0.005***	

Note: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. T-statistics are reported in parentheses and are based on robust standard errors.

management earlier have relatively higher environmental awareness and are more willing to increase corporate environmental investment. However, for firms in low-polluting industries, lower environmental pressure may lead to low environmental awareness and low willingness to participate in environmental governance investment. Therefore, we predict that in low-polluting industries, executives may place less emphasis on environmental performance, making it more

likely that D&O insurance will crowd out corporate environmental investment.

We divide listed companies into high-polluting and low-polluting companies based on industry codes ¹ and regress Model

¹ Industry codes B, C, and D are classified as high-polluting industries.

1 again. In column (1) of Table 5, we can find that the coefficient of DO in high-polluting companies is not significant. The possible reason for this is that, after a long period of development, firms in high-polluting industries have achieved some success in environmental management and therefore have limited marginal contribution to continued investment in the environment. In column (2) of Table 5, we can find that the coefficient of DO is significantly negative at the 5% level. It means that the disincentive effect of D&O insurance on environmental investment is more pronounced in low-polluting industries, which suggests that firms in low-polluting industries are more environmentally unaware and in these companies, D&O insurance is more likely to be used as a tool for selfish purposes by managers.

In addition, corporate environmental investment may be influenced to some extent by industry competition. When firms face fierce market competition, the conflict between their economic and environmental interests becomes evident, which leads to a more significant inhibitory effect of D&O insurance on corporate environmental investment. This is reflected in two ways. On the one hand, fierce market competition compresses the profit margins of enterprises and prompts them to reduce costs. After reaching the legal requirements of environmental investment, firms in a fiercely competitive environment are often reluctant to make too much environmental investment and are more concerned about whether the firm can gain more market share and economic benefits. This is because of the strong externality associated with environmental investment. Furthermore, excessive investment in environmental protection will increase the cost of enterprises, which is not conducive to a favorable position in fierce competition. Therefore, reducing high-cost environmental protection investments may be a means for firms to control costs. On the other hand, the appraisal of the performance of managers mainly emphasizes financial performance and neglects environmental performance. Therefore, when the market is more competitive, to avoid a decline in profits that affects performance appraisal, managers have more incentives to cut cost expenditures and reduce product costs, thus maintaining high compensation and monetary benefits, which crowd out environmental investments. Hence, we predict that the inhibitory effect of D&O insurance on corporate environmental investments is more pronounced in a more competitive market.

We use the Herfindahl–Hirschman index (HHI) of operating income to measure the competitiveness of industries. We divide the sample into two groups of high and low competition based on the median of the HHI and performed a group regression. The results in columns (3)–(4) of Table 5 show that the DO coefficient is not significant in low-competitive industries, whereas it is significantly negative in highly competitive industries. These findings indicated that the more competitive the market, the more the executives of the

TABLE 6 Political connection tests.

Variable	PC = PC_dum	PC = PC_level
	EI _{i,t+1}	EI _{i,t+1}
	(1)	(2)
DO	−0.6817*** (−3.0315)	−0.6875*** (−3.0861)
DO × PC	1.2363*** (3.2101)	0.3550*** (3.6584)
PC	−0.3026** (−2.3856)	−0.1000*** (−2.6719)
Constant	−6.5442*** (−3.8692)	−6.4708*** (−3.8190)
Control	Yes	Yes
Industry	Yes	Yes
Year	Yes	Yes
Adj. R ²	0.4676	0.4685
N	1008	1008

Note: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. T-statistics are reported in parentheses and are based on robust standard errors.

insured companies focus on economic interests, which leads to less environmental investment.

5.3 Political connection tests

According to the resource dependency theory, the government possesses important resources for the development of enterprises. Therefore, enterprises need to shape their relationship with the government for their long-term development (Wan and Luo, 2006). We expect that politically connected firms will actively respond to government policies and enhance corporate environmental investments to maintain their political and social capital. Accordingly, we further examine the impact of political connections on the relationship between D&O insurance and corporate environmental investment. Drawing on Jia et al. (2019) and Luo and Liu, (2019), we use PC_dum and PC_level to proxy political connections. Among them, PC_dum is a dummy variable that equals one if the chairman of the board or the CEO has served or is currently serving as a member of government departments, the National People's Congress of China (NPC), or the Chinese People's Political Consultative Conference (CPPCC), and 0 otherwise. PC_level is a fixed-order variable that takes values between 1 and 4, depending on the degree of political ties at the county,

city, province, and country levels, respectively. Otherwise, it takes the value 0.

Table 6 presents the results of political connection tests. Column 1) shows that the coefficient of the interaction term $DO \times PC$ ($PC = PC\_dum$) is positive and significant at the 1% level, suggesting that the negative effect of D&O insurance on environmental investment is attenuated for firms with political connections. The coefficient of $DO \times PC$ ($PC = PC\_level$) is also positive and significant at the 1% level in column (2). This finding suggests that higher levels of political connections mitigate the negative effect of D&O insurance on environmental investment.

6 Conclusion and recommendations

6.1 Conclusion

Based on the background of D&O insurance in China, this study uses data from A-share listed firms in China as a sample to study the impact of D&O insurance on corporate environmental investment. The results indicate the following: (1) D&O insurance is negatively associated with corporate environmental investment, which reveals the negative impact of D&O insurance on corporate environmental governance. (2) Executive monetary private benefits play a fully mediating role in the relationship between D&O insurance and corporate environmental investment, whereas non-monetary private benefits play no role. (3) The negative effect is more pronounced in low-polluting and highly competitive industries, indicating that the impact of D&O insurance on corporate environmental investment varies with the industry characteristics. (4) Political connections mitigate the negative relationship between D&O insurance and corporate environmental investment, and the higher the level of political connections, the more pronounced the mitigation effect, indicating that political-business relations play an important role in the corporate environmental governance process.

6.2 Recommendations

Our findings offer several practical recommendations. First, it is necessary to provide a favorable environment for D&O insurance governance. Enterprises should improve their internal governance and strengthen the supervision and punishment of executives displaying self-interested behavior, to prevent them from harming corporate environmental investment due to economic interests. However, insurance companies should also actively play an external governance function, for example, by increasing premiums, setting restrictive contract terms, and through ongoing monitoring to restrain the self-interested

behavior of executives and encourage corporate participation in environmental governance.

Second, because the inhibitory effect of D&O insurance on corporate environmental investment is more significant in low-polluting and highly competitive industries, corresponding environmental governance incentives should be formulated according to the industry characteristics. For high-polluting industries, environmental governance should be continuously increased and environmental management should not be relaxed. Even in low-polluting industries, executives should improve their environmental awareness and social responsibility and increase environmental investment. In addition, companies can also incorporate environmental performance into executive performance appraisals, so that executives increase their emphasis on environmental responsibility, whether they are in a high- or low-polluting industry. For an industry with fierce competition, due to the gradual improvement in the awareness of consumers about environmental protection, enterprises can increase investment in the research and development of green products to obtain new profit growth points. At the same time, the government can also provide tax incentives for corporate environmental investment and other behaviors that are beneficial to the environment, thereby reducing the cost pressure on enterprises and enabling them to better cope with the fierce market competition.

Finally, the government should realize that most enterprises are still in the stage of being forced to accept environmental governance and that their willingness to enhance environmental investment is insufficient. Therefore, in future environmental protection work, the government should fully consider the economic and regulatory feasibility of corporate environmental investment. In terms of economic feasibility, the government can provide appropriate financial and policy support for environmental investment enterprises and encourage them to invest in green research and development to improve their environmental performance, while maintaining economic performance. Regarding regulatory feasibility, the government should enrich the environmental regulatory tools and improve the market-oriented environmental regulatory tools, such as pollution permits and emission trading rights. Thus, improving the market mechanism of environmental investment can promote the transformation of the corporate environmental investment from passive to active.

Data availability statement

Publicly available datasets were analyzed in this study. These data can be found at: Chinese Research Data Services Platform and China Stock Market and Accounting Research Database.

Author contributions

JL: conceptualization, validation, resources, data curation, and writing the original draft. YJ: methodology, software, writing—review and editing, and visualization. SG: review and editing and supervision. All authors contributed to the manuscript and approved the submitted version.

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Appendix A Variable definitions.

Variable	Definition
EI	The natural logarithm of the amount of environmental investment
DO	A dummy variable that equals 1 if a firm purchases D&O insurance in a given year, and 0 otherwise
Size	The natural logarithm of a firm's total assets
Lev	The total debt divided by total assets
Roa	Net income divided by total assets
Cfo	Net cash flow of operating activities divided by total assets
Growth	Total assets growth rate
Board	The natural logarithm of a firm's board
Indep	The proportion of independent directors on a firm's board
Top1	The shareholding ratio of the largest shareholder
Msh	The shareholding ratio of the management
Age	The natural logarithm of the years of establishment of a firm

Appendix B VIF multicollinearity test.

Variable	VIF	1/VIF
Lev	2.01	0.497032
Size	2.00	0.500924
Roa	1.84	0.542538
Board	1.57	0.636805
Indep	1.49	0.669355
Cfo	1.35	0.738394
Msh	1.23	0.814811
Growth	1.22	0.817257
DO	1.18	0.849812
Top1	1.11	0.901747
Mean VIF	1.50	

Appendix C Balance test after PSM.

Variable	Unmatched	Mean		t% Reduc	t-test	
	Matched	Treated	Control	% Bias	t	p> t
Size	U	24.387	22.696	123.30	12.400	0.000
	M	23.932	23.777	11.30	0.790	0.433
Lev	U	0.520	0.449	38.30	3.530	0.000
	M	0.508	0.473	18.70	1.190	0.236
Cfo	U	0.065	0.060	8.50	0.830	0.407
	M	0.066	0.063	5.70	0.350	0.728
Growth	U	0.127	0.166	-16.30	-1.430	0.152
	M	0.117	0.112	2.00	0.170	0.866
Board	U	2.256	2.159	49.70	4.920	0.000
	M	2.242	2.260	-9.60	-0.600	0.549
Indep	U	0.377	0.375	4.20	0.370	0.709
	M	0.373	0.365	15.10	1.070	0.284
Top1	U	43.401	36.707	41.60	4.220	0.000
	M	41.138	42.003	-5.40	-0.340	0.735
Msh	U	0.011	0.047	-43.10	-3.400	0.001
	M	0.014	0.016	-2.70	-0.250	0.803
Age	U	2.929	2.806	43.00	3.990	0.000
	M	2.899	2.917	-6.60	-0.450	0.652

¹Industry codes B, C, and D are classified as high-polluting industries.



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National poverty alleviation strategy and policy regulation exemption: A quasi-natural experiment based on the green credit guidelines

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This paper evaluates the real effects of the environmental policy at the firm level. Using the promulgation of the "Green Credit Guidelines" and national poverty alleviation strategy as a quasi-natural experiment, we find that: 1) the Guidelines significantly inhibit the scale and maturity of debt financing for polluting companies; 2) the participation of enterprises in poverty alleviation efforts can effectively offset the restraining influence of the Guidelines. Our results are robust for parallel trend assumption and propensity score matching estimation. Further, we find that state-owned enterprises have decreased more significantly. These results indicate that the national poverty alleviation strategy could play a role in debt financing for polluting companies. Thus providing timely implications for regulators concerned with environmental protection.

KEYWORDS

national poverty alleviation strategy, policy regulation exemption, green credit guidelines, corporate finance, scale of corporate debt, maturity of corporate debt

1 Introduction

Since the reform and opening up, China's economic development has made remarkable achievements, but the original economic development model has also produced serious environmental pollution, which is not sustainable. These influences not only restrict the development of China's economy, but also seriously damage the health of Chinese residents. On 24 February 2012, the China Banking Regulatory Commission (CBRC) issued the Green Credit Guidelines¹, requiring Chinese financial institutions to support the development of green and low-carbon economy, improve the level of green credit financial services, and strengthen the ability to support green credit debt.

1 "Green credit policy" and Green credit Guidelines in the text refer to the same policy.

Since its introduction, the green credit policy has achieved good results, restraining the bank credit of high energy consumption and high pollution industries², optimizing the industrial structure, and effectively preventing financial risks. But with the proposed political task of targeted poverty alleviation, are enterprises involved in poverty alleviation exempted? At present, there is little literature on this aspect.

On the one hand, working to alleviate poverty has long been a high priority for the Chinese government and an important part of its vision for a well-functioning society. Targeted poverty reduction is a Chinese political term, first proposed by General Secretary Xi Jinping in 2013, that refers to a new form of corporate social responsibility. Corporations send signals to the market by disclosing relevant social responsibility information such as targeted poverty alleviation efforts, which can not only reduce the degree of information asymmetry and highlight their positive financial status and development prospects, but also establish a responsible corporate image and enhance their social reputation. Participating in such efforts gains the attention of both the market and potential investors, and thus can make a positive impact on improving the financing environment of enterprises.

On the other hand, enterprises the participating to alleviate poverty reduce the cash flow of enterprises to a certain extent. When enterprises need cash, they need to raise more funds by issuing stocks or bonds, thus deepening the financing constraints of enterprises. Does enterprise participating in poverty alleviation alleviate or strengthen financing constraints?

Our results suggest three main findings. First, the Guidelines significantly inhibit the scale and maturity of debt financing for polluting companies. The scale of corporate financing loans decreased by 2.6–3%, and the scale of long-term loans decreased by about 4.8%. Second, Corporate participation in poverty alleviation can offset the inhibitory effect of the Green Credit Guidelines. Enterprises that do not participate in poverty alleviation have their financing scale decreased by about 3% due to the “Green Credit Guidelines” policy. Third, we find that state-owned enterprises have decreased more significantly in Corporate participation in poverty alleviation can offset the inhibitory effect of the Green Credit Guidelines. Enterprises that do not participate in poverty alleviation have their financing scale decreased by about 3% due to the “Green Credit Guidelines”

policy. These results indicate that the national poverty alleviation strategy could play a role in debt financing for polluting companies.

This paper contributes to the literature on participation in poverty alleviation work in China. Our analysis is one of the few to explore the micro-mechanisms by which participation in poverty alleviation affects the actual economic activities of businesses. It provides a new perspective for research into the factors that affect the financing of Chinese enterprises.

Second, we contribute to the literature on the determinants of corporate financing. A better understanding of how environmental policy determines corporate financing is particularly important given the significant role environmental issues play in China and worldwide. We show that environmental policy significantly affects corporate financing.

In addition, this paper provides timely inspiration for policy-makers concerned about the impact of environmental policies on corporate behavior and calls for enterprises to actively participate in poverty alleviation work.

The rest of the paper is organized as follows. [Section 2](#) describes the institutional background, [section 3](#) explains the data and variables, and [section 4](#) analyzes the empirical results. [Sections 5](#) offers further analyses, [section 6](#) presents the test results for robustness and [section 7](#) concludes.

2 Institutional background and research hypothesis

2.1 The impact of green credit policies on corporate financing

The China Banking Regulatory Commission issued the Green Credit Guidelines in 2012 for a variety of reasons: to implement the combination of regulatory and industrial policies of the “12th Five-Year Plan”, to promote the development of green credit business within banking financial institutions, to adjust credit structures, to prevent environmental pollution risks caused by enterprises, and to avert potential social risks. According to these guidelines, financial institutions should promote green credit through three means. First, they should support a green and low-carbon circular economy and strictly control the scale of loans to “two high and one overcapacity” industries.³ Second, they

² According to the green credit guidelines, industries with high pollution, high energy consumption and excess capacity will be defined as polluting enterprises. According to China Securities Regulatory Commission 2012 industry classification standard. Industry codes include: C25, C26, C30, C31, C32, C33, C34 and D44.

³ The two industries refer to those with high pollution and energy consumption, whereas overcapacity refers to one with excess capacity. These industries mainly include steel, paper, electrolytic aluminum, plate glass, wind power and photovoltaic manufacturing industries (photovoltaic power generation, unlike the manufacturing industry, is not one of the these industries, and in fact is a clean energy industry encouraged by the state).

should optimize credit structures by restricting overall loans to prevent lending capital to companies that are not good environmental stewards. Third, they should improve the image of the finance industry by adjusting loan policies to encourage environmental responsibility (Fang and Li, 2019).

Developed countries in the West have taken the lead in applying green credit policies to the process of economic development. The evaluation criteria for credit review included whether the company pollutes and harms the environment (Pérez-Orive, 2016; Ye and Fang, 2021). Wu et al. (2017) point out that in green credit the quality of environmental information disclosure by firms has become the deciding factor for financial institutions. At the same time, more relaxed and convenient credit policies are given to environmentally-friendly enterprises so as to limit the development of businesses that pollute and realize the purpose of policies guiding the allocation of credit toward enterprises that are committed to preserving the environment (Xia and Liming, 2019).

Developing green credit policies is an innovative financial method that combines credit policies with environmental protection objectives (Labatt, 2002) that not only help Chinese banks and other financial institutions optimize social resources but also encourage companies to disclose their environmental responsibilities. The policy can assist companies in obtaining greater credit support through reducing environmentally damaging behavior. In China, the impact has been such that commercial banks and other financial institutions provide more loans for environmentally-friendly or energy-saving firms (Aizawa and Yang, 2010; Zhang et al., 2011; Liu et al., 2017). Therefore, the green credit policy has made important contributions to the “greening” of the Chinese economy and society. By the end of 2020, the green credit balance of 21 major Chinese banks had exceeded 11 trillion yuan, with the loan balance and growth scale of green transportation, renewable energy, energy conservation and environmental protection projects leading the way.

Green credit has spurred considerable academic interest and study. Some research has looked at issues with the development and implementation of such policies. In the early stages of the green credit revolution in China, commercial banks often had difficulty assessing risks when implementing green credit policies because finance workers lacked professional knowledge of what the policies were or how they worked (Ye, 2008; Zhang et al., 2011). Many green credit policies were not implemented efficiently. For example, to circumvent the constraints and restrictions of the green credit policy, some polluting companies turned to private lending and other methods of fund raising, running counter to the desired result.

With the gradual spread of green credit policies in developed countries, researchers made comparisons across international boundaries, summarizing the experiences of a range of countries (Jiang and Xu, 2016; Zhou et al., 2017). They highlight that, while

following guidance set by other countries may be a rational way to implement China's green credit policies, the government must first establish sound regulatory mechanisms to optimize the industrial economic structures. On this note, Yu and Wang (2021) talk of how China's strengthening environmental regulations is way for the governments to optimize its industrial economic structures as the economy moves from one of rapid growth into the stage of high-quality development.

In a different stream of researchers, other scholars have tended toward investigating the effects and outcomes of green credit initiatives as opposed to the early stages of development and implementation. For example, Cai (2013) used data from listed companies in polluting industries, such as papermaking, mining and electricity, to test the effectiveness of green credit policies. They find that such policies help banks to assess credit targets, thereby supporting the notion that green credit policies can promote the development of a green Chinese economy (Hee and Lyon, 2011). Su and Lian (2018) took the implementation of the 2012 Green Credit Guidelines as an exogenous event, constructed a quasi-natural experiment, and used the DID method to examine the actual changes in the investment and financing behavior of polluting companies before and after the implementation of the policy. The research conclusions show that after implementing the guidelines, impetus to invest in large heavy-polluting SOEs was significantly reduced, and the financing costs for those companies had significantly increased. All the above findings indicate that green credit significantly inhibits investment into polluting companies.

The 19th National Congress proposed that green development is the logical outcome of sustainable development, and green finance offers an important avenue in China's pursuit of building an ecological civilization. So how does green credit, as the main financing channel for green corporate projects, affect the growth of the green economy? Xie and Liu (2019) used a directional distance function and panel data for 30 provinces in China from 2006 to 2017 to calculate the green economic growth index of each region. The research results show that green credit policies significantly promote Chinese economic growth and that increasing the degree of marketization and fiscal decentralization would be conducive to promoting further green economic growth. Li et al. (2021) conducted an empirical analysis on the impact of green finance on the industrial structure based on the urban panel data from 2010 to 2019 using the grey correlation analysis method, and concluded that the development of green finance can optimize the industrial structure. Ouyang (2021) measured the development of green finance at the provincial level and calculated the green economic growth index. The research results show that the green credit policy has a significant role in promoting the growth of the green economy, and the improvement of the degree of marketization and fiscal decentralization is conducive to promoting the growth of the green economy. In addition, Zhang and Ge

(2021) used the double difference method to explore the role of green finance policy on internal resource allocation and optimization of enterprises in heavily polluting industries, using the green credit guidelines issued in 2012 as an exogenous shock. Research shows that green financial policies can significantly improve the efficiency of resource allocation within heavily polluting industries and promote green economic development.

Most of the mentioned studies focus on the macro- and meso-levels of the environmental effects of green credit policies. However, the specific implementation targets of macro policies are micro-level concerns, which are under-explored in the literature. Hence, with this research, we have studied the impact of green credit policies on enterprises at the micro-level, and especially how the scale of corporate debt financing and credit terms affects the policy outcomes.

According to the “Green Credit Guidelines” policy, banking financial institutions will promote green credit from three aspects: First, to increase support for a green, low-carbon and circular economy, and to control the issuance of credit to outdated production capacity. Second, to pay attention to preventing environmental and social risks. Third, banks focus on own environment and social performance. It can be seen from this that the Green Credit Guidelines aim to limit the scale and duration of loans to polluting and backward productivity companies. At the same time, the policy intends to increase support for a green low-carbon circular economy by redistributing credit resources while strictly controlling the “two highs and one overcapacity”⁴ credit supply.

Accordingly, we propose the following hypotheses

H1. The Green Credit Guidelines have significantly inhibited the debt financing for polluting enterprises.

2.2 The impact of enterprise participation in poverty alleviation

As an emerging market economy, the government maintains tight monopolistic controls over market resources, which means companies cannot fully rely on the market to acquire all the resources they may need to operate. In other words, enterprises heavily depend on the government for resources, such as finance credit resources. Social exchange theory holds that human behavior is governed by exchange activities that bring rewards.

Policy resources can take many forms, from fiscal and tax subsidies to exemptions, from rights issues by government departments to enter high-barrier regulated industries to better financing and credit environments. Under the leadership of the government, companies participating in targeted poverty alleviation not only help the government fulfill their social goals but also establish a connection between the company and the government. This leads many companies to use the relationships they hold with government to improve their business development environment and reduce the barriers they face to growth.

In reality, however, information asymmetry means stakeholders may only be able distinguish between different enterprises through the signals associated with various social behaviors. Some studies have discussed the positive impact of environmental information disclosure on firm credit financing (Li et al., 2019). Participating in poverty alleviation initiatives sends a different signal about what aspects of corporate social responsibility are important to a firm. Therefore, its influence on financing constraints may also be difference, as discussed next.

First, one of the prerequisites for a company to engage in alleviating poverty is that it is meeting its own daily operating needs and ensuring sufficient cash flow while disclosing information about the firm’s sound financial status to the outside world. Beyond the hypocrisy of a poor, badly run company attempting to help others alleviate these same problems, sound fiscal management and transparent reporting allows external actors to assess the enterprise’s operations and develop a more accurate understanding of its workings. Investors’ trust on capital funding increases, therefore, relieving financing constraints.

Second, in the context of the Chinese national economy, the government and SOEs occupy a dominant position. Enterprises exchange resources with the government by fulfilling their social responsibilities and gain financial support in return (Wang et al., 2020). The 2016 “Ten thousand enterprises help ten thousand villages” policy document⁵ states that relevant departments should proactively provide services, information, financing and other support to enterprises participating in poverty alleviation. Companies can also issue special corporate bonds for poverty alleviation through the exchange bond market (referred to as “poverty alleviation bonds”). These measures have given poverty-alleviating enterprises certain unique financing options, which means enterprises can get

⁴ The “two highs” refer to the resource-based industries with high pollution and high energy consumption; the overcapacity industries are those with overcapacity.

⁵ “Ten thousand enterprises to help ten thousand villages” is designed to mobilize private enterprises to help poor villages, speed up the process of poverty alleviation, contribute to the development and growth of the non-public sector of the economy, and complete the task of building a prosperous society in all respects.

TABLE 1 Definitions of variables.

Variable	Symbol	Measure of variables
Scale of corporate debt financing	<i>L1</i>	The sum of short-term and long-term loans accounts for the proportion of total liabilities
Scale of corporate short-term debt financing	<i>Short1</i>	The ratio of the sum of short-term loans to the company's total liabilities
Scale of corporate long-term debt financing	<i>Long1</i>	The ratio of the sum of long-term loans to the company's total liabilities
Indicator of industry pollution attributes	<i>Pollute</i>	1 indicates a polluting industry and 0 otherwise
Capital structure	<i>LEV</i>	The ratio of total liabilities to total assets
Profitability of a company	<i>ROA</i>	Pre-tax profit/Total assets
Firm age	<i>AGE</i>	2009 minus the year the company was established
Total assets	<i>SIZE</i>	The log form of total assets
Property rights	<i>STATE</i>	1 for state-owned and 0 otherwise
The largest shareholder	<i>LargestH</i>	The percentage of shares held by the largest shareholder
The top ten shareholders	<i>TopTenH</i>	The shareholding ratio of the top ten shareholders

TABLE 2 Descriptive statistics.

Variable	Obs	Mean	Std. Dev	Min	Max
<i>L1</i>	12,089	0.336	0.221	0	0.825
<i>Short1</i>	13,619	0.203	0.182	0	0.732
<i>Long1</i>	12,378	0.132	0.164	0	0.689
<i>Pollute</i>	14,973	0.191	0.393	0	1
<i>FP</i>	14,973	0.699	1.850 ^a	0	13.922
<i>LEV</i>	14,971	0.495	0.211	0.070	1.016
<i>ROA</i>	14,973	0.042	0.058	-0.175	0.229
<i>AGE</i>	14,973	0.251	1.168	0	3.332
<i>SIZE</i>	14,717	22.454	1.496	11.348	28.636
<i>STATE</i>	34,917	0.547	0.434	0	1
<i>LargestH</i>	14,718	37.086	15.832	8.320	77.230
<i>TopTenH</i>	14,718	57.263	16.930	20.710	93.900
<i>DEBT COST</i>	15,831	-0.146	0.370	-2.963	0.453

^aBecause: 1. Data on poverty alleviation was only released in 2016; 2. Many enterprises are not involved in poverty alleviation.

funding support from banks and the government for their poverty alleviation efforts while simultaneously addressing any financing constraints they might be experiencing.

Third, as an informal system, Confucian culture has subtly played a guiding role in Chinese thought and behavior, and exerted an important influence on all aspects of Chinese society, economy and politics (Fu and Tsui, 2003; Zhang, 2013). In terms of its specific impact on enterprises, Confucian culture helps to restrain the encroachment of small and medium shareholders' interests, reduce company agency costs, and improve agency efficiency and corporate performance (Du, 2015; Gu, 2015).

From a subjective point of view, Confucian culture enhances the altruistic motivation of enterprises to fulfill their social responsibilities. Entrepreneurs with social preferences are more concerned about the public's

TABLE 3 Empirical results of green credit policy on the scale and maturity of Corporate Debt Financing.

Variables	(1)	(2)	(3)	(4)
	Corporate debt scale		Corporate debt maturity	
	<i>L1</i>	<i>L2</i>	<i>Short1</i>	<i>Long1</i>
<i>Pollute* Post</i>	-0.030*** (-4.56)	-0.026*** (-6.96)	0.019*** (3.32)	-0.048*** (-9.49)
<i>LEV</i>	0.235*** (19.10)	0.427*** (61.11)	0.165*** (16.26)	0.086*** (9.20)
<i>ROA</i>	-0.194*** (-6.57)	-0.153*** (-9.13)	-0.189*** (-7.70)	-0.027 (-1.17)
<i>AGE</i>	0.098* (1.91)	0.125*** (4.29)	0.035 (0.77)	0.065 (1.63)
<i>SIZE</i>	0.037*** (14.62)	0.022*** (15.04)	0.007*** (3.51)	0.029*** (14.93)
<i>STATE</i>	-0.008 (-0.87)	0.007 (1.34)	-0.021*** (-2.83)	0.014** (2.06)
<i>LargestH</i>	0.001*** (4.17)	0.000*** (3.69)	0.000** (2.16)	0.001*** (3.89)
<i>TopTenH</i>	-0.000 (-0.65)	-0.000* (-1.87)	-0.000 (-1.63)	0.000 (0.01)
Industry	Y	Y	Y	Y
Year	Y	Y	Y	Y
Firm	Y	Y	Y	Y
Observations	12,087	12,087	13,617	12,376
<i>R</i> ²	0.382	0.135	0.093	0.1031

Notes: *t* statistics in parentheses, **p* < 0.10, ***p* < 0.05, ****p* < 0.01.

evaluation of their individuals, so the enterprises they operate are often more inclined to actively undertake social responsibilities (Li & Song, 2015). Confucian culture helps to

TABLE 4 Empirical results on the corporate debt for participate in poverty alleviation.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Participation in poverty alleviation				Non-participation in poverty alleviation			
	<i>L1</i>	<i>L2</i>	<i>Short1</i>	<i>Long1</i>	<i>L1</i>	<i>L2</i>	<i>Short1</i>	<i>Long1</i>
<i>Pollute* Post</i>	0.375*** (2.67)	0.194*** (2.61)	0.318** (2.25)	0.112 (1.01)	-0.031*** (-4.47)	-0.025*** (-6.29)	0.017*** (2.88)	-0.047*** (-9.01)
<i>LEV</i>	0.461*** (7.72)	0.565*** (17.91)	0.322*** (7.07)	0.154*** (3.35)	0.232*** (17.68)	0.422*** (56.60)	0.163*** (15.02)	0.082*** (8.36)
<i>ROA</i>	-0.168 (-1.51)	-0.183*** (-3.10)	-0.259*** (-3.10)	-0.013 (-0.15)	-0.190*** (-6.13)	-0.156*** (-8.83)	-0.174*** (-6.67)	-0.021 (-0.89)
<i>AGE</i>	0.011 (0.21)	-0.015 (-0.55)	-0.061 (-1.50)	-0.001 (-0.01)	0.109** (2.11)	0.133*** (4.53)	0.044 (0.95)	0.065 (1.64)
<i>SIZE</i>	0.045** (2.15)	0.020* (1.79)	0.013 (0.77)	0.032* (1.91)	0.044*** (15.96)	0.026*** (16.79)	0.013*** (5.69)	0.030*** (14.57)
<i>STATE</i>	-0.035 (-0.63)	-0.010 (-0.36)	-0.030 (-0.76)	-0.001 (-0.02)	-0.009 (-0.98)	0.004 (0.85)	-0.025*** (-3.25)	0.017** (2.38)
<i>LargestH</i>	0.001 (0.72)	0.001 (1.23)	0.001 (1.20)	-0.000 (-0.45)	0.001*** (2.98)	0.000** (2.37)	0.000 (1.17)	0.001*** (3.56)
<i>TopTenH</i>	0.001 (0.94)	0.000 (0.64)	0.000 (0.16)	0.001 (1.12)	0.000 (0.55)	-0.000 (-0.55)	-0.000 (-1.30)	0.000 (1.63)
<i>Industry</i>	Y	Y	Y	Y	Y	Y	Y	Y
<i>Year</i>	Y	Y	Y	Y	Y	Y	Y	Y
<i>Firm</i>	Y	Y	Y	Y	Y	Y	Y	Y
<i>Observations</i>	1,349	1,349	1,688	1,458	10,738	10,738	11,929	10,918
<i>R²</i>	0.414	0.161	0.141	0.047	0.376	0.137	0.090	0.108

t statistics in parentheses, **p* < 0.10, ***p* < 0.05, ****p* < 0.01.

improve the altruistic preference of entrepreneurs, thereby enhancing the intrinsic motivation of enterprises to fulfill their social responsibilities.

From an objective point of view, Confucian culture exerts public opinion pressure on enterprises to fulfill their social responsibilities. Traditional culture will form a strong external public opinion pressure on enterprises (Bi et al., 2015). With the development of the times, the Chinese public's awareness of social responsibility has been continuously enhanced, and the calls for enterprises to fulfill their social responsibility are getting louder and louder.

Thousands of years of Confucian culture in China have had a profound impact on corporate social responsibility. Social responsibility theory believes that the purpose of enterprise operation is not limited to the pursuit of profit. While taking responsibility for shareholders and employees, it is also responsible for consumers, communities and the environment. That is to say, it emphasizes attention to human values and contributes to the environment and society. Enterprises that actively participate in poverty alleviation are more likely to establish a good reputation and reputation, and gain the

recognition and support of the public. Therefore, creditors will recognize companies participating in poverty alleviation projects and are more willing to lend to these companies.

From the basis, we propose the following hypothesis:

H2. The participation of enterprises in poverty alleviation efforts can effectively offset the restraining influence of the "Green Credit Guidelines and Policies" on polluting enterprise financing constraints.

3 Data

3.1 Data and sample selection

To investigate the effect of the Green Credit Guidelines on corporate financing and the impact of corporate poverty alleviation behavior on their financing, we constructed a sample based on Chinese companies listed on the Shanghai and Shenzhen stock exchanges from 2009 to 2019. The period begins in 2009 to allow 3 years prior to 2012 for the DID

TABLE 5 Empirical results on green credit policy and the financing cost.

Variables	(1)	(2)	(3)
	—	Participation in poverty alleviation	Non- participation in poverty alleviation
	<i>DEBTCOST</i>	<i>DEBTCOST</i>	<i>DEBTCOST</i>
<i>Pollute* Post</i>	0.026** (2.11)	0.000 (0.01)	0.027** (2.06)
<i>LEV</i>	0.131*** (4.88)	0.015 (0.40)	0.135*** (4.66)
<i>ROA</i>	-0.155** (-2.47)	-0.010 (-0.16)	-0.158** (-2.37)
<i>AGE</i>	-0.004 (-0.05)	-0.274*** (-18.10)	-0.005 (-0.06)
<i>SIZE</i>	-0.015** (-2.41)	-0.006 (-0.71)	-0.017** (-2.46)
<i>STATE</i>	0.019 (0.99)	-0.003 (-0.10)	0.023 (1.11)
<i>LargestH</i>	-0.001 (-1.44)	-0.000 (-0.68)	-0.001 (-1.40)
<i>TopTenH</i>	-0.000 (-0.17)	0.000 (0.94)	-0.000 (-0.26)
Industry	Y	Y	Y
Year	Y	Y	Y
Firm	Y	Y	Y
Observations	8,698	618	8,080
<i>R</i> ²	0.021	0.036	0.022

t statistics in parentheses, **p* < 0.10, ***p* < 0.05, ****p* < 0.01.

estimation (the first year the Green Credit Guidelines were implemented). The targeted poverty alleviation and financial data of enterprises was taken from the CSMAR database. The values is set to 0 if the companies have not participated in or disclosed poverty alleviation. The industries classified as polluting were taken from the standard list in the Green Credit Guidelines.

Lastly, the samples were screened for exclusion according to several criteria. Special treatment (ST) companies were eliminated. Companies in the finance industry were also excluded because their listing and reporting requirements are significantly different from other companies. Further, the main continuous variables for all remaining companies are winsorized at the 1% level to eliminate the effects of extreme values. The final sample consisted of 14,973 firm-year observations.

3.2 Methodology and variables

Empirical studies on the effects of policies commonly rely on a DID model—hence, our choice to use a DID analysis to explore

the effects of the Green Credit Guidelines on corporate financing. The basic regression model was estimated as:

$$L_{it} = \beta_0 + \beta_1 Post_t \times Pollute_i + \beta_2 X_{it} + \eta_i + \gamma_t + \mu_j + \varepsilon_{ijt} \quad (1)$$

The explained variable *L* represents the scale and maturity of debt financing. The sum of short-term and long-term loans accounts for the proportion of total liabilities is used as a robustness test and is represented by *L1*. The ratio of the sum of short-term and long-term loans to the company's total assets was used as the explanatory variable to measure the scale of corporate debt financing, denoted as *L2*. In addition, we also used the ratio of the sum of short-term loans to the company's total liabilities as an explanatory variable to measure the scale of corporate short-term debt financing, denoted as *Short1*. Likewise, *Long1* represents the ratio of the sum of long-term loans to the company's total liabilities.

The explanatory variable in the model is an interactive item *Post_t × Pollute_i*. *Post_t* represents the dummy variable before and after the implementation of the Green Credit Guidelines. Since

TABLE 6 Empirical results the heterogeneity of ownership.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	SOEs				Non-SOEs			
	<i>L1</i>	<i>L2</i>	<i>Short1</i>	<i>Long1</i>	<i>L1</i>	<i>L2</i>	<i>Short1</i>	<i>Long1</i>
<i>Pollute* Post</i>	-0.035*** (-4.81)	-0.026*** (-6.41)	0.021*** (3.34)	-0.055*** (-9.57)	-0.023 (-1.48)	-0.027*** (-3.13)	-0.011 (-0.83)	-0.021* (-1.77)
<i>LEV</i>	0.277*** (16.67)	0.464*** (49.62)	0.176*** (12.46)	0.116*** (9.03)	0.238*** (11.61)	0.422*** (37.29)	0.177*** (10.94)	0.064*** (4.23)
<i>ROA</i>	-0.201*** (-5.22)	-0.203*** (-9.39)	-0.214*** (-6.51)	0.006 (0.22)	-0.191*** (-3.98)	-0.092*** (-3.47)	-0.165*** (-4.29)	-0.085** (-2.37)
<i>AGE</i>	0.186*** (4.20)	0.161*** (6.48)	0.096** (2.43)	0.067** (2.18)	-0.242*** (-2.93)	-0.096** (-2.11)	-0.053 (-0.74)	-0.204*** (-3.29)
<i>SIZE</i>	0.028*** (7.00)	0.018*** (8.12)	-0.007** (-2.00)	0.029*** (9.41)	0.036*** (8.13)	0.019*** (7.63)	0.011*** (3.13)	0.025*** (7.64)
<i>STATE</i>		-0.711*** (-10.44)	0.000 (.)	-0.859*** (-9.09)	0.000 (.)	0.000 (.)	0.000 (.)	0.000 (.)
<i>LargestH</i>	0.001*** (3.02)	0.000* (1.81)	0.000 (1.16)	0.001*** (3.41)	0.001 (1.51)	0.000** (2.11)	-0.000 (-0.28)	0.001*** (2.89)
<i>TopTenH</i>	-0.000*** (-1.51)	-0.000*** (-2.87)	-0.000** (-2.22)	-0.000 (-0.08)	0.001* (1.72)	0.000 (1.05)	0.000 (0.51)	0.000 (1.22)
Industry	Y	Y	Y	Y	Y	Y	Y	Y
Year	Y	Y	Y	Y	Y	Y	Y	Y
Firm	Y	Y	Y	Y	Y	Y	Y	Y
Observations	7,689	7,689	8,313	7,866	4,398	4,398	5,304	4,510
<i>R</i> ²	0.144	0.406	0.101	0.127	0.146	0.388	0.115	0.112

t statistics in parentheses, **p* < 0.10, ***p* < 0.05, ****p* < 0.01.

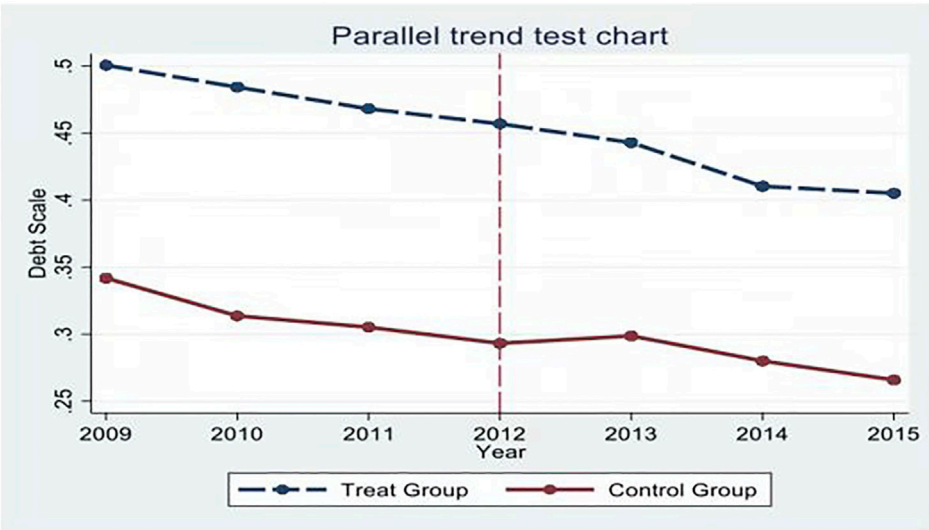


FIGURE 1
Parallel trend test chart.

TABLE 7 Bootstrap of green credit policy on corporate debt financing.

Variables	(1)	(2)	(3)	(4)
	<i>L1</i>	<i>L2</i>	<i>Short1</i>	<i>Long1</i>
<i>Pollute* Post</i>	-0.028*** (-2.59)	-0.026*** (-3.92)	0.018* (1.73)	-0.046*** (-4.74)
<i>LEV</i>	0.238*** (9.67)	0.422*** (33.10)	0.159*** (8.81)	0.087*** (6.58)
<i>ROA</i>	-0.253*** (-5.67)	-0.182*** (-5.04)	-0.228*** (-5.73)	-0.054* (-1.88)
<i>AGE</i>	0.004 (1.05)	0.004** (2.20)	0.004 (1.18)	0.004* (1.68)
<i>SIZE</i>	0.027*** (6.56)	0.014*** (5.15)	0.001 (0.29)	0.023*** (10.12)
<i>STATE</i>	-0.030*** (-2.81)	-0.010 (-1.60)	-0.026*** (-3.02)	-0.006 (-1.11)
<i>LargestH</i>	0.000 (1.23)	0.000 (0.76)	0.000 (0.92)	0.000 (0.57)
<i>TopTenH</i>	-0.000 (-0.61)	-0.000 (-1.00)	-0.000* (-1.72)	0.000 (1.01)
Industry	Y	Y	Y	Y
Year	Y	Y	Y	Y
Observations	12,087	12,087	13,617	12,376
<i>R</i> ²	0.118	0.369	0.081	0.091

t statistics in parentheses, **p* < 0.10, ***p* < 0.05, ****p* < 0.01.

the Green Credit Guidelines were released in 2012, the years from 2012 to 2019 inclusive are flagged as 1, while 2009, 2010, and 2011 are set as 0. *Pollute_i* is an indicator of industry pollution attributes, where one indicates a polluting industry and 0 otherwise.

To ensure that the results were not driven by the heterogeneity of the firm, we added the following control variables to cover firm characteristics, denoted as *X_{it}*: 1) firm size (*SIZE*), defined as the log form of total assets; 2) capital structure (*LEV*), defined as the ratio of total liabilities to total assets; 3) firm age (*AGE*), calculated as 2009 minus the year the company was established; 4) the profitability of a company (*ROA*), assessed as pre-tax profit/total assets; 5) the percentage of shares held by the largest shareholder (*LargestH*); 6) the shareholding ratio of the top ten shareholders (*TopTenH*); 7) a dummy variable (*STATE*) indicating whether the firm is a state-owned enterprises, (i.e., one for state-owned and 0 otherwise). ε_{it} is an error term. In addition, firm individual effect, industry effect and time effect are also controlled in our estimation.

The definitions of related variables are presented in Table 1.

3.3 Descriptive statistics

The descriptive statistics of the variables are shown in Table 2. As shown, the average value of corporate debt financing (*L1*) was 0.336 with maximum values of 0.825. This is a clear demonstration of the significant differences in the extent of debt financing for different enterprises, providing motivation for the basis of this study. Further, polluting enterprises accounted for 19.1 percent. The maximum return on total assets (*ROA*) was 0.229 with a minimum of only -0.175, profitability varies considerably across the sample. Variables such as the asset-liability ratio (*LEV*) and enterprise size (*SIZE*) show that the financial position and size of the different enterprises also varies.

4 Empirical results and analysis

4.1 Empirical analysis of green credit policy on the scale of corporate debt financing

The impact of green credit policies on the scale of corporate financing debt is shown in Table 3. The explained variable *L1* represents the debt financing scale of the companies, and *L2* is used for robustness test. It can be seen from columns 1 and 2 of Table 3 that, regardless of how the extent of corporate debt was measured, the coefficient of the interaction term *Pollute*Post* was always negative and significant at the 1% confidence level. This indicates that the effect of the Green Credit Guidelines has indeed achieved the goal of curbing the scale of debt financing of polluting industries. Additionally, the estimated effect of the green credit policy on the extent of debt for the polluting companies was about 3%. This result is consistent with hypothesis H1 and the results of previous studies.

From the perspective of control variables, the coefficients such as enterprise size (*SIZE*) and return on assets (*ROA*) are also consistent with the results of previous studies. The return on assets (*ROA*) of an enterprise is negatively correlated with its debt financing maturity. That is because profitable firms use more internal capital and less external debt.

From the results in columns 3 and 4 of Table 3, we can see the impact of the Green Credit Guidelines on the firms' short-term and long-term loans. The *Pollute*Post* coefficient in column 3 is positively significant, suggesting that the Green Credit Guidelines restrict long-term loans while focus companies to use short-term loans. It is also a reflection of Green Credit Guideline loan constraint effect. This is very likely because the Guidelines emphasize that

TABLE 8 Bootstrap of corporate participation in poverty alleviation on corporate debt financing.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Participation in poverty alleviation				Non-participation in poverty alleviation			
	<i>L1</i>	<i>L2</i>	<i>Short1</i>	<i>Long1</i>	<i>L1</i>	<i>L2</i>	<i>Short1</i>	<i>Long1</i>
<i>Pollute* Post</i>	0.172*** (4.16)	0.092*** (2.59)	-0.110 (-0.77)	0.263*** (23.02)	-0.029** (-2.45)	-0.025*** (-3.27)	0.017* (1.82)	-0.045*** (-5.21)
<i>LEV</i>	0.318*** (8.92)	0.499*** (15.91)	0.199*** (4.85)	0.098*** (3.90)	0.237*** (12.40)	0.418*** (32.05)	0.159*** (8.69)	0.086*** (5.34)
<i>ROA</i>	-0.295*** (-5.18)	-0.219*** (-4.38)	-0.327*** (-5.51)	-0.092 (-1.02)	-0.248*** (-5.30)	-0.183*** (-5.66)	-0.216*** (-7.61)	-0.050 (-1.38)
<i>AGE</i>	0.003 (0.47)	0.002 (0.52)	-0.003*** (-18.92)	0.009** (1.99)	0.002 (0.45)	0.003 (1.27)	0.004 (1.42)	-0.000 (-0.02)
<i>SIZE</i>	-0.013** (-2.09)	-0.009*** (-3.01)	-0.019*** (-3.76)	0.005*** (4.93)	0.031*** (8.70)	0.016*** (5.20)	0.004 (1.17)	0.024*** (11.05)
<i>STATE</i>	-0.029 (-1.32)	-0.008** (-1.98)	-0.022 (-0.88)	-0.012 (-0.99)	-0.031*** (-3.15)	-0.011 (-1.62)	-0.029*** (-3.91)	-0.004 (-0.70)
<i>LargestH</i>	-0.000 (-0.32)	-0.000 (-0.15)	0.001** (2.04)	-0.000 (-1.21)	0.000 (0.43)	0.000 (0.14)	0.000 (0.38)	0.000 (0.14)
<i>TopTenH</i>	-0.000 (-0.29)	-0.000 (-0.53)	-0.001* (-1.70)	0.000 (0.92)	0.000 (0.03)	-0.000 (-0.31)	-0.000* (-1.71)	0.000** (2.02)
Industry	Y	Y	Y	Y	Y	Y	Y	Y
Year	Y	Y	Y	Y	Y	Y	Y	Y
Observations	1,349	1,349	1,688	1,458	10,738	10,738	11,929	10,918
<i>R</i> ²	0.111	0.379	0.112	0.010	0.120	0.363	0.077	0.095

t statistics in parentheses, **p* < 0.10, ***p* < 0.05, ****p* < 0.01.

financial institutions should limit the environmental and social risks of granting credit to polluting companies by shortening the debt maturity. This result is consistent with hypothesis H1.

With respect to the control variables, the findings are consistent with previous results.

4.2 Empirical analysis of corporate participation in poverty alleviation and corporate debt financing

For this portion of the analysis, we divided the enterprises into two groups: those who had participate in poverty alleviation projects and those who had not. The regression results are shown in Table 4. Column 1 lists the scale of debt held by the participating enterprises. From the *Pollute*Post* coefficients, we can see that the scale of debt for these companies has increased by about 20–30% (significant at 1%). This shows that corporate participation in poverty alleviation can counteract the

path to debt financing, all but exempting the inhibitory effects brought about by the Green Credit Guidelines. In column 5, *Pollute*Post* is about -3% and significant at 1%. Coupled with a significant downward trend over the period, this result shows that the policies are working: enterprises who do not participate in poverty alleviation are not receiving as much credit.

We further explored whether corporate participation in poverty alleviation affected credit maturity. Columns 3 and 4 show the results for the enterprises involved in poverty alleviation. The *Pollute*Post* coefficients for both increased, which demonstrates that companies participating enterprises can extend the terms of their debt repayment to relatively long periods. Columns 7 and 8 show the results for the non-participating firms. The *Pollute*Post* coefficients show that long-term loans decreased by about 4.7% while short-term loans increased. Thus, for those not interested in supporting the government's agenda, the loan terms have been shortened.

In terms of the control variables, consistent with the previous results, the company's asset-liability ratio (*LEV*) is positively correlated with the company's debt financing

TABLE 9 Replacing metrics of green credit policy on corporate debt financing.

Variables	(1)	(2)	(3)	(4)
	<i>Short2</i>	<i>Short3</i>	<i>Long2</i>	<i>Long3</i>
<i>Pollute* Post</i>	0.006* (1.85)	-0.181 (-0.80)	-0.033*** (-11.22)	-0.808*** (-3.01)
<i>LEV</i>	0.279*** (49.99)	8.313*** (20.97)	0.144*** (26.78)	8.081*** (16.45)
<i>ROA</i>	-0.122*** (-9.05)	-4.297*** (-4.47)	-0.026** (-1.99)	-2.308* (-1.93)
<i>AGE</i>	0.061** (2.43)	3.439* (1.93)	0.066*** (2.89)	2.370 (1.13)
<i>SIZE</i>	0.002* (1.87)	2.289*** (27.44)	0.021*** (18.73)	3.089*** (30.06)
<i>STATE</i>	-0.003 (-0.66)	-0.658** (-2.25)	0.011*** (2.88)	0.522 (1.48)
<i>LargestH</i>	0.000 (1.35)	0.007 (0.95)	0.000*** (4.09)	0.014 (1.56)
<i>TopTenH</i>	-0.000** (-2.11)	-0.009 (-1.48)	-0.000 (-1.08)	0.005 (0.68)
Industry	Y	Y	Y	Y
Year	Y	Y	Y	Y
Firm	Y	Y	Y	Y
Observations	13,617	13,617	12,376	12,376
<i>R</i> ²	0.273	0.185	0.177	0.238

t statistics in parentheses, **p* < 0.10, ***p* < 0.05, ****p* < 0.01.

maturity and significant at the 1% level. Return on assets (ROA) is negatively correlated to the debt financing period.

Overall, the results show that, against a background of increasingly serious environmental pollution, the state has introduced green credit and the scale and maturity of financing credit for polluting companies has been significantly regulated. However, the participation of enterprises in poverty alleviation efforts can effectively offset the restraining influence of the “Green Credit Guidelines and Policies” on enterprise financing constraints. The above results are confirmed H2.

5 Further analysis

5.1 The analysis of the influence of green credit policy on the financing cost of enterprises

The main purpose of the green credit policy is to restrict financing to enterprises in polluting industries. However, beyond exploring the effectiveness of the green credit policy at achieving

its goal, we are also interested in the impact the green credit policy has on the cost of corporate financing. To explore this notion further, we conducted an empirical study following the methods of Zheng and Yan, 2016.

DEBTCOST was defined as *Financial expenses/(short-term borrowings + long-term borrowings + long-term borrowings due within 1 year + bonds payable)*.

To test this premise, we substituted DEBTCOST into the regression model and added control variables for year, industry, and the firms’ fixed effects. As shown in Table 5, the coefficients in the first column are positive and significant at the 5% level. In addition, from the results in columns 2 and 3, it can be seen that the financing cost of enterprises participating in poverty alleviation has not changed significantly. The financing cost of enterprises not participating in poverty alleviation has increased. Because the cost of credit financing is a part of the operating cost of a business. If the cost of financing increases, it will reduce the profit of the company. Therefore, the “Green Credit Guidelines” restrain the scale and duration of financing of enterprises by increasing the financing cost of enterprises.

5.2 The heterogeneity of ownership

The literature suggests that SOEs and enterprises will be protected by any political ties they have (Li et al., 2015). Driven by the Official Promotion Championship (Zhou, 2007), the impact of the quality of local environmental governance on local governments, and even officials, cannot be ignored. SOEs have always assumed important responsibilities in terms of employment resolution, charitable donations, and so on, because, in China, companies with political ties enjoy preferential treatment in the form of tax incentives and government subsidies (Zou, 2018). Therefore, it is interesting to examine the different effects of the Green Credit Guidelines on debt financing for SOEs versus non-SOEs and whether the green credit policy effects change simply because the target carries favor with the regulators.

For this analysis, we therefore considered the effect of each firm’s ownership structure on its debt financing. The results in Columns 1 of Table 6 is -0.035 and significant at 1% while -0.023 but not and significant in Columns 5 of Table 6. It shows that the financing scale of state-owned enterprises has decreased more significantly, which may be because most of the enterprises restricted by the green credit guidelines are in the coal and steel industries, and most of these enterprises are state-owned enterprises. Long-term lending has been curbed for both SOEs and non-SOEs. By contrast, Green Credit Guidelines has a higher restriction effect on SOEs bank loans than non-SOEs, but non-SOEs is also affected to a certain extent, indicating that

TABLE10 Replacing metrics of corporate participation in poverty alleviation.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Participation in poverty alleviation				Non-participation in poverty alleviation			
	<i>Short2</i>	<i>Short3</i>	<i>Long2</i>	<i>Long3</i>	<i>Short2</i>	<i>Short3</i>	<i>Long2</i>	<i>Long3</i>
<i>Pollute* Post</i>	0.136* (1.82)	-12.988** (-2.29)	0.089 (1.48)	3.348 (1.57)	0.005 (1.63)	-0.208 (-0.86)	-0.031*** (-10.38)	-0.706** (-2.46)
<i>LEV</i>	0.337*** (13.94)	12.207*** (6.67)	0.260*** (10.41)	6.279*** (5.85)	0.277*** (46.31)	8.404*** (19.40)	0.137*** (24.21)	8.406*** (15.67)
<i>ROA</i>	-0.152*** (-3.43)	-3.345 (-1.00)	-0.068 (-1.39)	3.134 (1.48)	-0.116*** (-8.08)	-4.012*** (-3.85)	-0.025* (-1.83)	-2.409* (-1.87)
<i>AGE</i>	-0.038* (-1.77)	1.365 (0.84)	-0.002 (-0.09)	-0.702 (-0.58)	0.069*** (2.70)	3.467* (1.89)	0.066*** (2.89)	2.369 (1.10)
<i>SIZE</i>	-0.004 (-0.46)	1.571** (2.37)	0.022** (2.34)	1.132*** (2.86)	0.006*** (4.88)	2.420*** (26.11)	0.022*** (18.20)	3.138*** (27.62)
<i>STATE</i>	-0.030 (-1.45)	-0.137 (-0.09)	0.009 (0.45)	-0.153 (-0.18)	-0.005 (-1.23)	-0.729** (-2.33)	0.012*** (2.89)	0.454 (1.20)
<i>LargestH</i>	0.001* (1.76)	0.042 (1.59)	-0.000 (-0.07)	-0.006 (-0.37)	0.000 (0.31)	0.003 (0.32)	0.000*** (3.53)	0.003 (0.34)
<i>TopTenH</i>	-0.000 (-0.24)	-0.067** (-2.40)	0.000 (1.00)	0.022 (1.30)	-0.000* (-1.78)	-0.005 (-0.72)	0.000 (0.61)	0.016* (1.85)
<i>Industry</i>	Y	Y	Y	Y	Y	Y	Y	Y
<i>Year</i>	Y	Y	Y	Y	Y	Y	Y	Y
<i>Firm</i>	Y	Y	Y	Y	Y	Y	Y	Y
<i>Observations</i>	1,688	1,688	1,458	1,458	11,929	11,929	10,918	10,918
<i>R²</i>	0.267	0.234	0.072	0.104	0.269	0.175	0.175	0.218

t statistics in parentheses, **p* < 0.10, ***p* < 0.05, ****p* < 0.01.

Green Credit Guidelines plays a good role in loan resource allocation.

6 Robustness tests

6.1 Parallel trend assumption

The validity of the DID approach depends on satisfying the key identifying assumption behind this strategy, the parallel trend assumption, which requires a similar trend in corporate debt scale during the pre-shock period for both the treatment and control groups. Therefore, the first robustness test is to examine the parallel trend assumption within our DID test.

Figure 1 provides the parallel trend test chart, which shows that, before the green credit policy was implemented, there was no significant difference between the extent of financing between the treatment and control groups. However, since the green credit policy took effect in 2012, there have been

significant differences in the extent of financing for the treatment and control groups. The consistency of this result with the previous analysis validates use the DID model to test the impact of green credit policies on corporate financing.

6.2 Bootstrapping the samples

Bootstrapping is a method, common to computer simulations, that is often used to solve statistical problems with large samples. The method prescribes that the given test be repeated multiple times with a new set of samples selected at random but with an equal probability of each sample in the original data set being selected. In this way, the average value of the statistics of 500 samples can be obtained by repeating the sampling 500 times. The mean calculated by this combination is more stable and more convincing than any result collected by analyzing all samples at once.

TABLE 11 T+1 Period of Green Credit Policy on Corporate Debt Financing.

Variables	(1)	(2)	(3)	(4)
	<i>f.L1</i>	<i>f.L2</i>	<i>f.Short1</i>	<i>f.Long1</i>
<i>Pollute* Post</i>	-0.035*** (-5.14)	-0.031*** (-7.09)	0.007 (1.26)	-0.040*** (-7.64)
<i>LEV</i>	0.078*** (5.75)	0.201*** (23.47)	0.071*** (6.56)	0.033*** (3.24)
<i>ROA</i>	-0.095*** (-2.99)	-0.138*** (-6.85)	-0.111*** (-4.27)	0.013 (0.53)
<i>AGE</i>	0.051 (1.14)	0.077*** (2.74)	0.057* (1.85)	0.037 (1.08)
<i>SIZE</i>	0.027*** (9.52)	0.024*** (13.44)	0.012*** (5.04)	0.016*** (7.60)
<i>STATE</i>	-0.004 (-0.38)	0.006 (1.02)	-0.013 (-1.59)	0.012* (1.65)
<i>LargestH</i>	0.001*** (3.07)	0.000** (2.56)	0.000* (1.84)	0.000** (2.50)
<i>TopTenH</i>	-0.000 (-0.94)	-0.000*** (-3.39)	-0.000 (-1.62)	-0.000 (-0.20)
Industry	Y	Y	Y	Y
Year	Y	Y	Y	Y
Firm	Y	Y	Y	Y
Observations	10,575	10,574	11,911	10,847
<i>R</i> ²	0.065	0.154	0.052	0.064

t statistics in parentheses, **p* < 0.10, ***p* < 0.05, ****p* < 0.01.

6.2.1 Bootstrap of green credit policy on corporate debt financing

The test results for robustness using the bootstrapping method are shown in Table 7. Regardless of how the independent variable corporate debt financing scale was measured, the coefficients for *Pollute* Post* in Columns 1 and 2 were always negative and significant. The coefficients in Column 3 indicate that the Guidelines have not had a significant impact on the company's short-term loans. However, *Long1* in Column 4 shows that the green credit policy has significantly reduced the scale of long-term loans. This finding suggests that it is very unlikely that DID estimated results in the main regression are purely driven by chance.

6.2.2 Bootstrap of corporate participation in poverty alleviation on corporate debt financing

To further test robustness, we again divided the sample into participating and non-participating companies. The regression results in Columns 1–2 of Table 8 show that the amount of debt financing have increased but only for companies participating in poverty alleviation projects.

Columns 5 and 6 show that, for non-participation firms, the overall amount of debt has dropped by about 2.5–2.9%. These results confirm that the results of the previous empirical analysis.

6.3 Replacement metrics

To validate the robustness of the empirical tests, we changed the method of measuring the dependent variable *L1* from the ratio of the sum of short-term and long-term loans to the company's total liabilities to instead of *L2*, calculated as the sum of short-term and long-term loans accounts for the proportion of total assets. Similarly, we originally calculated *Short1* as the ratio of the sum of short-term loans to the company's total liabilities. This method was replaced with two different formulae: *Short2* calculated as the ratio of the sum of short-term loans to the company's total assets, and *Short3* calculated as the log form of the total short-term debt plus 1. *Long1* from the ratio of the sum of long-term loans to the company's total liabilities was replaced with *Long2* as the ratio of the sum of long-term loans to the company's total assets and *Long3* as the log form of the total long-term debt plus 1. The regression results with these formulations are shown in Tables 9, 10. All results support the previous findings.

6.4 Robustness test of lag effect

To test for a lag effect, we replaced the dependent variable with the data sampled from the period *t*+1. All results support the previous findings. The regression results with these formulations are shown in Tables 11, 12. All results support the previous findings.

6.5 A robustness test to exclude the "municipalities effect"

The same policy often produces very different effects in different regions because certain municipalities are directly under the control of the Central Government. Therefore, we ran the tests without these regions and compared the results. The regions excluded were Beijing, Tianjin, Shanghai and Chongqing.

Our findings suggest that the results of the main regression are robust.⁶

⁶ Due to space limitations, the regression results were not presented. If necessary, it can be obtained from the author.

TABLE 12 T+1 period of Corporate Participation in Poverty Alleviation.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Participation in poverty alleviation				Non-participation in poverty alleviation			
	<i>f.L1</i>	<i>f.L2</i>	<i>f. Short1</i>	<i>f.Long1</i>	<i>f.L1</i>	<i>f.L2</i>	<i>f. Short1</i>	<i>f.Long1</i>
<i>Pollute* Post</i>	-0.162 (-0.85)	-0.066 (-0.57)	-0.209 (-0.31)	0.203** (1.98)	-0.035*** (-4.94)	-0.029*** (-6.35)	0.007 (1.22)	-0.040*** (-7.49)
<i>LEV</i>	-0.111 (-1.41)	0.019 (0.39)	-0.145** (-2.29)	-0.039 (-0.64)	0.077*** (5.41)	0.194*** (21.45)	0.074*** (6.49)	0.028*** (2.65)
<i>ROA</i>	-0.098 (-0.63)	-0.044 (-0.47)	0.061 (0.54)	-0.303** (-2.35)	-0.101*** (-3.05)	-0.148*** (-7.01)	-0.111*** (-4.08)	0.013 (0.50)
<i>AGE</i>	-0.011 (-0.15)	0.023 (0.50)	0.100 (1.59)	0.049 (1.38)	0.064 (1.42)	0.085*** (3.00)	0.081 (1.62)	0.040 (1.17)
<i>SIZE</i>	0.038 (1.31)	0.030* (1.76)	0.012 (0.51)	0.019 (0.81)	0.032*** (10.34)	0.027*** (14.03)	0.015*** (6.23)	0.017*** (7.43)
<i>STATE</i>	0.011 (0.19)	-0.011 (-0.32)	-0.025 (-0.62)	-0.007 (-0.18)	-0.007 (-0.71)	0.004 (0.63)	-0.016* (-1.89)	0.013* (1.77)
<i>LargestH</i>	0.001 (0.87)	0.000 (0.21)	0.001 (1.16)	-0.000 (-0.33)	0.000 (1.58)	0.000 (0.80)	0.000 (0.74)	0.000* (1.91)
<i>TopTenH</i>	-0.001 (-1.12)	-0.001* (-1.79)	-0.002** (-2.30)	0.001 (0.93)	0.000 (0.24)	-0.000** (-2.11)	-0.000 (-1.04)	0.000 (0.98)
Industry	Y	Y	Y	Y	Y	Y	Y	Y
Year	Y	Y	Y	Y	Y	Y	Y	Y
Firm	Y	Y	Y	Y	Y	Y	Y	Y
Observations	877	877	1,067	972	9,698	9,697	10,844	9,875
<i>R</i> ²	0.030	0.049	0.052	0.021	0.065	0.147	0.054	0.067

t statistics in parentheses, **p* < 0.10, ***p* < 0.05, ****p* < 0.01.

7 Conclusion

In this paper, we used the DID method to conduct an empirical analysis of the impact of China's Green Credit Guidelines on the debt financing of listed companies given corporate participation in poverty alleviation. From the findings we draw the following conclusions.

First, the Green Credit Guidelines significantly inhibit the scale and maturity of debt financing for polluting companies. The policy controls the size and duration of loans to polluting companies by increasing their financing costs. However, it may be that it gives companies some latitude to allocate resources to green innovation or move from a rapid growth mode to an intensive development posture.

Second, the enterprises actively participating in poverty alleviation are tending to circumvent the inhibitory effect of the Green Credit Guidelines on financing credit. The results provide evidence to suggest that these enterprises are using the sanctions in the guidelines to obtain financial support from banks and the government to overcome financing constraints. This insight enriches the research on poverty alleviation in China and

provides a new perspective for research into the factors that influence financing for Chinese enterprises.

Third, many researchers have pointed out that state-owned enterprises (SOEs) with political background enjoy preferential treatment in finance and financial subsidies. The question, then, is whether SOEs are receiving special treatment in the context of the green credit policy. In response to these doubts, we conducted a deeper analysis of the influence of a company's property rights and confirmed that SOEs are not receiving any particular special treatment. Thus, our overall conclusion is that China's green credit policy is largely achieving its stated goals.

For environmental protection and high-quality economic development, issues such as building a green financial system need to be solved urgently. We believe that rely on the existing financial information system to build a data sharing platform for relevant functional departments. Use modern means such as big data and blockchain to build a green information dynamic collection mechanism. Encourage enterprises to disclose environmental protection information, incorporate green credit ratings into assessment indicators, and improve enterprises' environmental awareness.

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

WW contributed to the study design, including the conceptualization and methodology, prepared datasets, and promoted project administration. JM contributed to the resources, data analysis, and original draft preparation. SL proposed revisions during the final draft of the paper. LL contributed to the study's organization, identified the research methods, and performed the review and editing of the manuscript. All authors read and approved the final manuscript.

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Does the government's environmental attention improve enterprise green innovation?—Evidence from China

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In recent years, governments worldwide have paid more attention to environmental issues, and green innovation is essential to balance economic growth and environmental sustainability. This article investigates the different impacts of the government's environmental attention on green innovation of heavy-polluting and non-heavy-polluting firms using the sample of listed firms in China from 2011 to 2019. We find that the relationship between the government's environmental attention and green innovation is consistent with the "U"-shape in heavy-polluting firms. However, the government's environmental attention positively impacts the green innovation of non-heavy-polluting firms. In addition, Fintech mitigates the negative effects of the government's environmental attention on green innovation in the short term while enhancing the positive effect of the government's environmental attention on green innovation in the long term for heavy polluting firms. Our article provides evidence and implications for environmental regulation in developing countries and urban areas.

KEYWORDS

government's environmental attention, green innovation, FinTech, heavy polluting firms, non-heavy polluting firms

1 Introduction

Over the past several decades, inappropriate human activities have been steadily increasing and influencing numerous climate extremes in every region of the world, according to the report published by the Intergovernmental Panel on Climate Change (IPCC, 2021). To deal with the contradiction between economic development and environmental protection, governments worldwide have focused on environmental issues and engaged firms' green production persistently (Zhang et al., 2011; Martín et al., 2020). Green innovation has long been recognized to be a critical factor in balancing economic growth and environmental sustainability. Several articles have examined the influencing factors of green innovation from the perspective of micro- and macro-level (Gollop and Robert, 1983; Amore and Bennedsen, 2016), particularly the effects of environmental regulations and related policies on green innovation (Porter and Linde,

1995; Zhang et al., 2011; Song et al., 2020; Wang et al., 2020; Fang et al., 2021). However, few of them investigated the impact of the government's environmental attention on green innovation.

Initially, "attention" was a topic for psychologists. Jones (2010) introduced "attention" to government decision-making and proposed an attention-driven model for policy selection. He argues that decision-makers must differentiate the significance of information based on their attention and then make decisions accordingly, demonstrating that when policymakers' attention shifts, government decisions follow suit. Due to the limited attention span of policymakers, when policymakers' attention is focused on environmental protection, associated issues are more likely to be motivators behind the policy and related behavior (Wen and Du, 2018). Policy and institutional changes determine enterprise behavior (La Porta et al., 1998), particularly in a transitioning country like China, where firms are exposed to greater external uncertainty and must stay sensitive to changes in regulations to seize business opportunities. Therefore, changes in government regulations significantly impact the investment and financing behaviors of firms (Khanna and Rivkin, 2001; Liu et al., 2022). When the government focuses attention on environmental protection, businesses may anticipate potential institutional changes and alter behaviors accordingly. This allows us to explicitly link the government's environmental attention to corporate green innovation.

Depending on the different mechanisms, the government's environmental attention may promote or inhibit green innovation. Heavy polluters have a greater demand for emissions than non-heavy polluters and are, therefore, the primary targets of environmental regulation (Matthews and Denison, 1981; Gray, 1987). Moreover, polluting firms have a lot of pressure on green transition, which is essential to enhancing product competitiveness (Wong, 2012). Hence, most existing research on green innovation focuses on heavy polluting firms (Wu et al., 2018; Li and Xiao, 2020). Although non-heavy-polluting firms are not the primary targets of pollution control, this does not mean that non-heavy polluting firms will not engage in green innovation. For instance, firms in the industry like automobile manufacturing are not highly polluting; however, they can still optimize their production through environmentally responsible innovation. Existing research ignores the impact mechanism of green innovation on non-heavy-polluting firms. So, what are the differences between the impact of the government's environmental attention on green innovation in heavy-polluting and non-heavy-polluting firms?

A related question is whether Fintech influences the relationship between the government's environmental attention and green innovation. The existing literature provides evidence that Fintech increases the accessibility of financial services, alleviates financing constraints, and thereby boosts the green innovation of firms (Li et al., 2020; Tan et al., 2022). Yet, it remains unclear whether Fintech will affect the

relationship between the government's environmental attention and green innovation.

Using the data of A-share firms listed in the Shanghai and Shenzhen stock exchanges in China from 2011 to 2019, combined with the dataset of the government's environmental attention in 274 cities, we investigate the different impacts of the government's environmental attention on green innovation of heavy-polluting and non-heavy-polluting firms. Additionally, we explore the moderating effect of Fintech on the relationship between the government's environmental attention and green innovation. Moreover, we focus on the government's environmental attention mechanism for green innovation through two channels: "crowding-out effect" and "innovation compensation."

The following content is organized as follows: Section 2 provides the literature review. The theoretical framework and research hypotheses are presented in Section 3. Section 4 presents the methodology, and Section 5 describes the analysis of the empirical results. Finally, Section 6 summarizes the conclusions and implications.

2 Literature review

2.1 Attention and policy behavior

"Attention" was initially a topic of interest to psychologists, but it has become an essential concept in the disciplines of management and organizational behavior (Wang, 2013). Attention is "the process by which managers selectively focus on certain information and ignore others" (Simon, 1947). Attention allocation necessitates the rapid determination of what is urgent and essential within the limit of decision-makers' cost constraints. Some researchers have investigated the economic effects of changes in managers' and the public's attention (Zheng et al., 2013; Liu and Wang, 2014). Jones (2010) introduced "attention" to government decision-making and proposed an attention-driven model for policy selection. He argues that decision-makers must prioritize the significance of information based on their attention and then make decisions accordingly, demonstrating that when policymakers' attention shifts, government decisions follow suit.

Existing research has examined the measurement of government attention. Chen and Chen (2018) and Wen (2014) measure the government's focus on innovation, entrepreneurship, and essential public services in China, respectively, using text analysis techniques on government work reports. Flavin and Franko (2017) use introduction data from state legislatures to measure government attention and discover that state legislators are less likely to act on an issue when it is prioritized by low-income citizens than by wealthy citizens. Some scholars assess the government's environmental attention. Wang and Li (2017) analyze the government work

reports in 30 Chinese provinces and cities between 2006 and 2015, using text analysis to examine the changes in the government's attention to ecological and environmental issues. It has been discovered that the local government's attention to ecological and environmental issues has gradually increased and that this attention is consistent with that of the central government.

A large strand of research has evaluated the effects of the government's environmental attention on pertinent policies and administration. Using the cognitive dynamics theory of psychology, Wen and Du (2018) investigate the impact of changes in the central government's environmental attention on government environmental policies and explain the process using "concept-motivation-guidance" logic. Wang and Wu (2021) examine the effect of government-public attention congruence on environmental governance and conclude that environmental governance is more effective when government and public attention are congruent. Shen et al. (2020) investigated the effect of government ecological attention on environmental governance performance in the Beijing-Tianjin-Hebei region between 2005 and 2020, demonstrating that environmental protection attention is most effective at enhancing environmental governance performance. Huang et al. (2022) investigated the effects of the Chinese government's environmental attention on ambient pollution. The results indicate that increasing the government's environmental attention can reduce air pollution. When governments shift their attention from "pursuing GDP growth" to "green and low-carbon development," they can significantly reduce carbon emissions, which can boost economic growth in the long run according to Hu and Wang (2022).

2.2 Influencing factors on green Innovation

Existing literature has examined the factors that contribute to green innovation. Some studies have investigated the micro-level factors of green innovation, such as firm-level environmental management (Li et al., 2019), corporate governance (Amore and Bennedsen, 2016), environmental perceptions of executives (Lin and Chen, 2017), financial constraints (Aghion et al., 2009), and stakeholder pressure (Song et al., 2020).

A portion of the literature investigates the macro-level factors that influence green innovation, focusing primarily on government environmental regulations and green innovation-related policies. Regarding the impact of environmental regulation on green innovation, some neoclassical economics theories propose that environmental regulation inhibits green innovation by increasing the cost of environmental compliance for firms (Gollop and Robert, 1983). It is primarily due to the "crowding-out effect" of environmental regulations on firms'

investments in green technological innovation due to rising compliance costs, production costs, and sewage costs (Matthews and Denison, 1981; Gray, 1987; Palmer et al., 1995; Bai et al., 2019). Nevertheless, several studies have demonstrated the beneficial effects of environmental regulations on green innovation. According to Porter and Linde (1995), well-designed environmental regulations promote green innovation. By compelling or incentivizing firms to invest more in R&D to enhance their ability to reduce pollution and product technology content, regulations create innovation compensation and competitive advantage (Zhang and Vander, 1995; Jaffe and Palmer, 1997; Zhang et al., 2011; Jing and Zhang, 2014; Guo, 2018; Li et al., 2018; Fang et al., 2021).

Recent research indicates that the relationship between environmental regulation and green innovation is not linear but "U"-shaped in terms of inhibition or promotion. Zhang et al. (2011) contended that the "U"-shaped relationship between environmental regulation and green innovation is because the positive effects of "innovation compensation" and the negative effects of "compliance costs" are not synchronized, and the positive effects lag behind the negative ones. Thus, a "U"-shaped relationship exists between a given level of environmental regulation and technological innovation (Shen, 2012; Xie et al., 2017; Fan et al., 2020).

Several researchers have investigated the heterogeneity of environmental policies' effects on green innovation. Some studies have demonstrated the significant effects of new environmental protection laws, the central environmental protection inspection system, and the environmental protection target responsibility system on corporate green innovation (Wang et al., 2020; Song et al., 2022). Some academics also believe that market-based environmental regulations, such as emission taxes, environmental protection taxes, and environmental subsidies, have a greater effect on fostering green innovation (Weitzman, 1974; Nordberg-Bohn, 1999; Requate, 2005; Cai and Li, 2018). Several articles have demonstrated that financial technology can enhance the accessibility of financial services, alleviate corporate financing constraints, optimize the precision and efficiency of external and internal capital allocation, and thereby promote corporate green innovation (Li et al., 2020; Tan et al., 2022).

Our article contributes to the literature by first exploring the effect of the government's environmental attention on green innovation. Prior research has examined the impact of the government's environmental attention on environmental protection policies (Wen and Du, 2018), the efficiency of environmental governance (Wang and Li, 2017; Wang and Wu, 2021), environmental investment, and carbon emissions (Zheng et al., 2013; Huang et al., 2022). Yet, few studies have examined the impact of the government's environmental attention from the standpoint of green innovation. Second, this article investigates the different mechanisms of the impacts of the government's environmental attention on green innovation of heavy polluting and non-heavy polluting firms.

Since heavy polluters are the primary focus of environmental management, most existing green innovation studies have centered on these companies (Wu et al., 2018; Li and Xiao, 2020). However, the existing studies have disregarded the mechanism of the government's environmental attention on green innovation in non-heavy polluting firms. Lastly, we further explore the moderating effect of Fintech on the relationship between the government's environmental attention and firms' green innovation. Although some scholars have investigated the impact of financial technology on firms' green innovation (Li et al., 2020; Tan et al., 2022), the effect of Fintech on the relationship between the government's environmental attention and firms' green innovation has been overlooked.

3 Hypothesis development

A local government work report is a policy issued by the local government that typically includes a review and summary of the government's work from the previous year, plans for the upcoming year, and resource allocation guidance. The report reveals "the focus of their work and where their resources flow." Thus, the government's work report is a significant indicator of the government's attention allocation or shift (Wen, 2014; Wang and Li, 2017).

According to the psychological cognitive dynamics theory, changes in government attention primarily reflect changes in government cognition, which is a vital force driving behavior and a precondition for institutional and policy changes. Due to the limited attention span of policymakers, when their attention is on environmental protection issues, social issues related to environmental protection are more likely to shape policy motives and drive the related policy behaviors (Wen and Du, 2018). Policy changes affect the behavior of businesses and vice versa. Firms always pay close attention to institutional shifts to identify opportunities and adjust their development strategy, investment and financing behavior, and business decisions promptly to accommodate policy shifts (Zhou, 1999; Khanna and Rivkin, 2001). Therefore, businesses can anticipate possible policy and institutional changes and adapt their behavior accordingly when the government demonstrates a growing concern for environmental protection by releasing public information.

As the government pays more attention to the environment, policymakers allocate their limited attention to addressing environmental issues, and institutions or policies change accordingly. As a result, the government is more likely to implement stringent environmental policies, increase environmental legislation and enforcement, and increase pressure on businesses to control emissions and protect the environment (Wen and Du, 2018; Shen et al., 2021), such as by establishing energy conservation and emission reduction

targets and increasing penalties for noncompliance. As a result, firms must purchase pollution-reducing equipment and incur operating expenses, in addition to paying higher taxes and environmental fines. It will undoubtedly increase the cost of sales and administrative expenses, reducing the firm's free cash flow and tightening its financing constraints, resulting in a "crowding-out effect" on investment in technological innovation (Matthews and Denison, 1981; Gray, 1987; Bai et al., 2019). Moreover, to pursue short-term profits, businesses typically limit their investments in green innovations, which are characterized by lengthy cycles, high costs, and substantial unpredictability (Gollop and Robert, 1983). Therefore, increased government environmental attention may harm green innovation in the short term.

While the government's environmental attention grows to a certain level, its positive impact on green innovation is felt over a longer period. First, with the increase of government's environmental attention, governments are more likely to increase environmental regulation, and the market will be more inclined to resource-saving and environment-friendly green products under reasonable regulations. With the awareness of increased government environmental attention, companies will choose to optimize resource allocation, develop green technology and equipment, and improve production processes and organizational management to enhance the green technology of their products according to Porter's theory (Porter and Linde, 1995). It will stimulate the "innovation compensation effect" of the company, resulting in environmental protection and performance growth, while companies without efficient green innovation are more vulnerable to being eliminated by the market (Zhang et al., 2011; Jing and Zhang, 2014). Second, with increased government environmental attention comes increased government financial budgets for environmental protection, such as increased financial allocations, environmental subsidies, green credit, and other local government-provided financial support for firms' environmental protection projects (Wen and Du, 2018; Li and Chen, 2022). Support from environmental protection funds can promote firms' green innovation, generate a "resource compensation effect," direct firms' green technology development, prompt firms to invest or purchase resources for green R&D activities, increase firms' green innovation investment, and thereby promote firms' green innovation (Yang et al., 2017; Huang et al., 2019). Lastly, an increase in the government's environmental attention indicates that the government is more inclined to provide resources and pays more attention to environmental issues. According to signaling theory, green innovation can assist businesses in obtaining a government-approved label, constructing a positive corporate image, and attracting more external resources to supplement themselves (Feldman and Kelley, 2006; Kleer, 2010). Therefore, the

government's increased focus on the environment can aid in increasing the level of green innovation among businesses.

When examining the effects of the government's environmental attention on green innovation, there are significant differences between the mechanisms for heavy polluters and non-heavy polluters. Heavy polluters have a greater demand for waste disposal and are the primary focus of environmental governance. As environmental regulation improves, waste disposal consumes a greater portion of cash flow and reduces green innovation investment (Matthews and Denison, 1981; Gray, 1987). In addition, the increased government attention to the environment makes it harder for heavy polluters to obtain loans and then tightens financing restrictions (Ding et al., 2020). Therefore, the negative effect of the government's increased environmental attention on green innovation is more significant in the short term for firms that heavily pollute. Nonetheless, as the government's environmental attention grows, polluting firms have more pressure to green transition, which is the essential path to enhancing product competitiveness. When the "innovation compensation effect" is greater than the "crowding-out effect," the government's environmental attention will spur green innovation. However, since the two effects are not synchronized, the negative effect tends to occur in the short term, whereas the performance of green innovation takes longer to be compelled. Consequently, increased government environmental attention decreases green innovation in the short term but increases green innovation in the long term (Zhang et al., 2011).

Based on the analysis presented earlier, we propose hypothesis 1 (H1):

H1. : The influence of the government's environmental attention on the green innovation of heavy polluting firms shows a U-shaped relationship.

Since non-heavy polluting firms are not the primary focus of pollution control, increasing the government's environmental attention does not significantly increase such environmental associated costs and expenses. Therefore, the negative effects of the increased government's environmental attention on green innovation can be negligible for firms that do not heavily pollute. Nevertheless, it does not imply that non-heavy polluting firms will not implement green innovation. Although ecological protection and environmental management are not heavy polluters, they can still promote green production through green innovation. On the one hand, green innovation has become a strategy for some businesses to obtain policy resources. These firms prefer green innovation that is easier and quicker to achieve, allowing them to obtain more government subsidies or tax rebates by disclosing green patent information. On the other hand, with the increasing government's environmental attention, the environmental awareness of both individuals, firms, and the government will be enhanced (Li and Zheng, 2016), and customers are more inclined to resource-saving

and environment-friendly green products. Green innovation can not only meet customers' needs and build a good reputation for the company but also improve product competitiveness and prevent environmental pollution (Kammerer, 2009; Li et al., 2015; Hou et al., 2021). With the growth of the government's environmental attention, non-heavy polluting firms foresee the business opportunities brought by green production and then perform green innovation. Therefore, the increase in the government's environmental attention has positively impacted the green innovation of non-heavy polluting firms.

Based on the analysis presented earlier, we propose hypothesis 2 (H2):

H2. : The government's environmental attention is positively associated with green innovation in non-heavy-polluting firms.

Financial technology can enhance the availability of regional financial services, alleviate the financing constraints of firms, and direct the precise flow of funds, thereby optimizing the precision and efficacy of external and internal capital allocation (Tan et al., 2022). Green innovation activities are characterized by high costs, lengthy timelines, and high levels of uncertainty. Thus, green innovation activities require greater financial support than others (Gollop and Robert, 1983). Suppose the enterprise's location city has a high level of financial technology. In that case, it can effectively reduce information asymmetry, alleviate resource mismatch (Tian et al., 2017), and provide financial support for the R&D of heavy polluters who need to implement green innovation. This advanced level of financial technology will mitigate the short-term negative effects of the government's environmental attention on green innovation. In the long term, it improves the efficiency of resource allocation, creates a favorable external financial environment, and aids heavy polluters in achieving the "innovation compensation effect" (Tan et al., 2022). Thus, a high level of financial technology augments the positive impact of the government's environmental attention on the green innovation of heavy polluters.

Based on the analysis presented earlier, we propose hypothesis 3 (H3):

H3. : Increased financial technology can mitigate the negative effects of the government's environmental attention on the green innovation of heavy polluting firms in the short term while enhancing the positive effect of the government's environmental attention on the green innovation of heavy polluting firms in the long term.

4 Methodology

4.1 Sample and data collection

In this article, we use the data of A-share companies listed in the Shanghai and Shenzhen stock exchanges from 2011 to

2019 and filter samples as follows: 1) exclude the samples that were ST, *ST, PT, and delisted during the sample period; 2) exclude the samples of financial companies; 3) exclude the samples with missing variables. Finally, we obtained 18,390 observed samples and performed tailing at the 1% and 99% levels for continuous variables. The other main variables are defined and measured as follows.

4.2 Measurement

4.2.1 Green innovation

The data on green innovation were obtained from the National Intellectual Property Patent Database of China. According to Song et al. (2020), we collected the patent information of the sample firms from 2011 to 2019 and matched them with the Green List of International Patent Classification, which was published by the World Intellectual Property Organization. Since patent application data are more stable than the number of patents granted, and the year of patent application could better reflect the actual innovation time than the year of patent grant, we use the total number of green patent applications (*GI_{Total}*) to measure the green innovation of firms. Furthermore, according to the type of green patents, we classify green patents into green invention patents (*GreIv*) and green utility model patents (*GreUm*). Meanwhile, to make the sample more consistent with the assumption of normal distribution, we use the natural logarithm of the number of green patent applications plus one to measure corporate green innovation, following Tan et al. (2022). In addition, green innovation has a time lag caused by research and development, so we use *t*+1 period green innovation data as the dependent variable.

4.2.2 Government's environmental attention

To measure the government's environmental attention (*GEA*), we use text analysis to obtain the frequency of environmental keywords used in government work reports, and the number of relevant words reflects the degree of attention given to a public issue by decision-makers (Wang and Li, 2017; Huang et al., 2022). The more frequently the words appear, the more attention the government pays to the issue. To ensure the completeness and continuity of the textual data, we first collected 274 city-level government work reports from 2011 to 2019, all of which were obtained from the official government websites. Second, we read 15 reports from different regions and years intensively to extract keywords related to environmental protection and sorted them by frequency (Shen et al., 2020). Then, we selected the top 15 keywords (Wang and Li, 2017), which were low carbon, environmental protection, air quality, green, PM2.5, COD, CO₂, PM10, ecology, emission, emission reduction, pollution, environmental protection, sulfur dioxide, and energy consumption. Third, we used software to sort the government work report documents word by word and count

the frequency of the abovementioned keywords. Finally, considering the influence of text length on the frequency of keywords, we standardized the index by dividing the frequency of keywords by the total number of words in the text and then multiplying by 100 to get the government's environmental attention (Huang et al., 2022).

4.2.3 The mediating variables

In order to measure the level of financial technology (*Fintech*) where the company is located, we used the number of companies in the finance and high-technology industries in the city to measure *Fintech* according to Tan et al. (2022). We obtained the number of companies that is financial and technological which were currently in existence and had been operating for 2 years through the advanced search function of the "Enterprise Search" website. Furthermore, considering *Fintech* is influenced by the level of local economic development, we adjusted the indicator by dividing the number of Fintech companies by the regional GDP.

4.2.4 The control variables

According to the related study by Lin et al. (2014), we control for the following variables (*controls*) in the model: firm size (*size*), the natural logarithm of the firm's total assets; firm age (*age*), firm's establishment time; leverage (*Lev*), the ratio of total liabilities to total assets; return of Asset (*Roa*), the ratio of net profit to average total assets; firm value (*TobinQ*), the sum of the market value of owner's equity and liabilities to total book assets; revenue growth (*growth*), the percentage of revenue growth; independent directors (*Indep*), the percentage of independent directors to board members; cash flow from operating activities (*cashflow*). As the level of economic development of the city may affect the firm's innovation capability, we control the city-level GDP (*Lngdp*), and we also control for year fixed effects (*year*), industry fixed effects (*industry*), and city fixed effects (*city*) in the model. All financial data of listed companies are obtained from the Wind database, and data on economic indicators at the city level are obtained from the China City Statistical Yearbooks.

4.3 Model

Based on the previous assumptions and variable settings, our benchmark regression model is set as follows:

$$GI_{i,t+1} = \alpha_0 + \alpha_1 GEA_{it} + \alpha_2 GEA_{it}^2 + \alpha Controls_{it} + \varepsilon_{it}, \quad (1)$$

$$GI_{i,t+1} = \beta_0 + \beta_1 GEA_{it} + \beta_2 GEA_{it}^2 + \beta_3 Fintech + \beta_4 Fintech * GEA_{it} + \beta_5 Fintech * GEA_{it}^2 + \beta Controls_{it} + \varepsilon_{it}, \quad (2)$$

where α and β are the coefficients of variables, i and t denote the enterprise and year, respectively, and $GI_{i,t+1}$ denotes the green

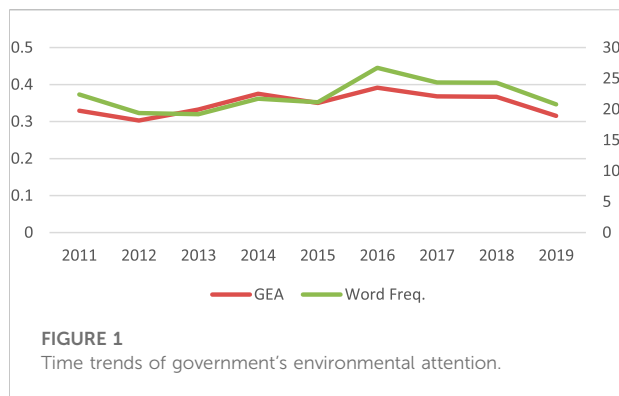


TABLE 1 Descriptive statistics.

Variable	N	Mean	Std.	Min	Median	Max
<i>GITotal</i>	18,390	0.299	0.744	0.000	0.000	6.874
<i>GreIv</i>	18,390	0.213	0.610	0.000	0.000	6.719
<i>GreUm</i>	18,390	0.168	0.527	0.000	0.000	5.347
<i>GEA</i>	18,390	0.357	0.128	0.029	0.351	1.239
<i>GEA</i> ²	18,390	0.144	0.102	0.001	0.123	1.535
<i>Fintech</i>	18,390	0.002	0.001	0.000	0.001	0.007
<i>Size</i>	18,390	22.139	1.294	19.525	21.956	26.395
<i>Age</i>	18,390	16.979	5.598	1.000	17.000	61.000
<i>Lev</i>	18,390	0.417	0.207	0.031	0.407	0.925
<i>Roa</i>	18,390	0.044	0.062	-0.415	0.041	0.222
<i>Growth</i>	18,390	0.180	0.443	-0.623	0.109	4.806
<i>Cashflow</i>	18,390	0.045	0.069	-0.200	0.045	0.257
<i>TobinQ</i>	18,390	2.003	1.336	0.815	1.588	17.676
<i>Indep</i>	18,390	0.375	0.053	0.308	0.353	0.600
<i>Lngdp</i>	18,390	8.803	1.095	4.399	8.878	10.549

innovation level of enterprise i in the next period, which is measured by three indicators: total number of green patent applications ($GITotal$), green invention patents ($GreIv$), and green utility model patents ($GreUm$), respectively; GEA_{it} denotes the primary term of the government's environmental attention in the city where enterprise i is located in year t ; GEA_{it}^2 denotes the secondary term of the government's environmental attention; $Fintech$ denotes the level of financial technology in the city in the model (2); $Controls_{it}$ denotes all control variables, and ε_{it} is the random error term.

4.4 Statistics

Figure 1 shows the mean values of the government's environmental attention and the environment-related word frequency in 274 cities in China from 2011 to 2019. The figure shows that the average GEA was falling from 0.33% to

0.30% during 2011–2012 and then raised to 0.37% in 2014. After that, it experienced volatile falling to 0.35% and rising to 0.39%, with 2 years stabilized at 0.37% and then fell to 0.32% in 2019. This indicates that although local governments were aware of the importance of environmental governance and have begun to focus on environmental protection issues, the growth of government's environmental attention is volatile and weak in sustainability, and local governments need to improve their environmental attention continuously.

Table 1 reports descriptive statistics for the variables in this article. The mean and median of $GITotal$ are 0.299 and 0, respectively, which means the data have serious right skewness, the green innovations of the firms are highly differentiated, and the overall innovation level is low. Compared with the number of $GreUm$, the mean and standard deviation of the number of $GreIv$ are larger, which indicates that firms are more positive to carry out green invention patents, but the differences in performance among individuals are more obvious. The mean and Std. of GEA are 0.357% and 0.128, respectively, which means the differentiation of the government's environmental attention among cities is not huge.

5 Empirical results

5.1 Benchmark regression

As in the previous analysis, the mechanisms of the government's environmental attention to green innovation are different between heavy polluting and non-heavy polluting firms. Hence, we divided the sample into heavy polluting and non-heavy polluting groups according to the Guidelines on Environmental Information Disclosure of Listed Companies issued by the Shanghai Stock Exchange. Table 2 reports the results of the benchmark regressions of the impact of the government's environmental attention on green innovation for heavy polluting and non-heavy polluting firms, respectively.

Columns (1) to (3) show the results for the sample of heavy polluting firms. The signs of the coefficients of GEA and GEA^2 are negative and positive, respectively, and are both significant at least at the 10% level, which demonstrates that as the government's environmental attention shifts from weak to strong, the impact it has on heavy polluters' green innovation will change from negative to positive. Therefore, the relationship between the government's environmental attention and green innovation is consistent with the "U"-shape, which can prove hypothesis H1. The results are significant in $GITotal$, $GreIv$, and $GreUm$, and the inflection points are 0.377, 0.343, and 0.432, respectively. The mean value of the existing government's environmental attention data is 0.357, which indicates that the government's environmental attention has started to promote green invention patents for heavy polluting firms, but the

TABLE 2 Effect of government's environmental attention on green innovation.

	Heavy-polluting firms			Non-heavy-polluting firms		
	(1)	(2)	(3)	(4)	(5)	(6)
	<i>GITotal</i>	<i>GreIv</i>	<i>GreUm</i>	<i>GITotal</i>	<i>GreIv</i>	<i>GreUm</i>
<i>GEA</i>	−7.777** (3.253)	−4.372* (2.441)	−3.405** (1.515)	0.487*** (0.166)	0.333** (0.135)	0.243* (0.137)
<i>GEA</i> ²	10.224** (4.295)	6.301* (3.229)	3.924** (1.832)	−0.478* (0.200)	−0.310 (0.165)	−0.262 (0.159)
<i>Size</i>	−0.598 (0.443)	−0.420 (0.394)	−0.179** (0.086)	−0.015** (0.006)	−0.011** (0.005)	−0.016*** (0.005)
<i>Age</i>	0.004 (0.026)	−0.000 (0.012)	0.004 (0.022)	0.001 (0.001)	0.000 (0.001)	0.000 (0.001)
<i>Lev</i>	1.598 (1.425)	1.013 (1.147)	0.585 (0.635)	−0.037 (0.032)	−0.008 (0.027)	−0.040 (0.025)
<i>Roa</i>	4.983 (3.600)	3.430 (2.769)	1.554 (1.857)	0.072 (0.085)	0.077 (0.073)	0.006 (0.062)
<i>Growth</i>	−0.131 (0.225)	0.002 (0.105)	−0.134 (0.185)	0.011 (0.008)	0.007 (0.006)	0.010 (0.006)
<i>Cashflow</i>	−2.712 (2.128)	−1.740 (1.800)	−0.972 (0.771)	−0.118* (0.070)	−0.054 (0.060)	−0.089* (0.054)
<i>TobinQ</i>	−0.322 (0.200)	−0.197 (0.122)	−0.125 (0.146)	−0.004 (0.004)	−0.003 (0.003)	−0.004 (0.003)
<i>Indep</i>	1.445 (4.034)	−0.544 (1.795)	1.990 (3.058)	0.007 (0.093)	0.030 (0.079)	−0.008 (0.078)
<i>Lngdp</i>	0.740 (0.637)	0.785 (0.484)	−0.045 (0.250)	0.007 (0.027)	0.011 (0.023)	−0.008 (0.021)
<i>_cons</i>	1.479 (7.238)	−1.930 (5.028)	3.410 (3.487)	0.171 (0.304)	0.052 (0.266)	0.419* (0.248)
<i>Year, industry, and city</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	4,920	4,920	4,920	13,479	13,479	13,479
<i>Adj.R</i> ²	0.012	0.009	0.012	0.058	0.039	0.044

Notes: *** and ** stand for significant levels of 1%, and 5%, respectively, and the values in parentheses are Std. Dev.

influence on the total number of green patents and green utility model patents has not reached the inflection point.

Columns (4) to (6) show the regression results for the sample of non-heavy polluters. The coefficients of government's environmental attention are 0.487, 0.333, and 0.243, respectively, and all of them are positively significant at a level of at least 10%, which indicates that the government's environmental attention has a positive effect on green innovation of non-heavy-polluting firms, and the impact is greater on green invention patents than on green utility model patents. The results indicate that the motivation of innovation for non-heavy-polluting firms is not only to strategically release "green signals" but also to foresee the business opportunities brought by green production. The results mentioned earlier are consistent with hypothesis H2.

It is worth noting that the regression coefficients of *GEA*² for non-heavy polluters are negative, but only the result of *GITotal* is significant in statistics, which means the regression result is not robust. The results demonstrate that the positive effect of *GEA* on green innovation gradually decreases with the increase in the government's environmental attention to non-heavy polluting firms, but the results are not robust to an inverted U-shaped trend. The possible explanation is that one of the purposes of green innovation for non-heavy polluting firms is to release green signals and obtain government resources, and when green innovation reaches the standard of obtaining government resources, the incentive for green innovation decreases (Zhu et al., 2022). Meanwhile, with the improvement of resource allocation efficiency, government resources will be allocated to firms with more green production needs, so when the

TABLE 3 Mediating effect test.

Heavy-polluting firms	(1)	(2)	(3)	(4)	(5)	(6)
	<i>GI</i> Total	<i>GreIv</i>	<i>GreUm</i>	<i>GI</i> Total	<i>GreIv</i>	<i>GreUm</i>
<i>GEA</i>	−14.940** (6.866)	−9.441* (5.868)	−5.499** (2.221)	−7.615** (3.241)	−4.218* (2.497)	−3.397** (1.460)
<i>GEA</i> ²	9.115* (8.090)	5.485 (6.915)	3.630 (2.618)	−0.509* (2.342)	−1.600 (1.482)	1.092 (1.424)
<i>Fintech</i>	0.144 (0.124)	0.094 (0.106)	0.050 (0.040)	0.305 (0.218)	0.206 (0.191)	0.099** (0.046)
<i>Fintech</i> × <i>GEA</i>	0.814*** (0.242)	0.578*** (0.207)	0.236*** (0.078)			
<i>Fintech</i> × <i>GEA</i> ²				1.048** (0.417)	0.766** (0.326)	0.282* (0.147)
_cons	−71.871*** (20.372)	−52.593*** (17.412)	−19.278*** (6.591)	−74.967* (42.259)	−54.851 (37.040)	−20.115** (9.207)
Control	Yes	Yes	Yes	Yes	Yes	Yes
Year, industry, and city	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	4,920	4,920	4,920	4,920	4,920	4,920
Adj. <i>R</i> ²	0.019	0.013	0.017	0.019	0.014	0.018

government's environmental attention reaches a certain level, its positive effect on green innovation for non-heavy polluting firms diminishes.

5.2 Mediating effects

Table 3 shows the regression results that added the interaction terms of financial technology level (*Fintech*), *GEA*, and *GEA*², respectively, in heavy-polluting firms. As the inclusion of interaction terms has serious multicollinearity problems that affect the regression results, therefore, we follow Su and Zhou (2019) to add the interaction terms separately. Focusing on the regression coefficients and significance levels of the interaction term *Fintech*×*GEA*, we find that the coefficients of the interaction term are significantly positive at the 1% level, and the coefficients are 0.814, 0.578, and 0.236, respectively. The results indicate that the increase of financial technology weakens the impact of the government's environmental attention on green innovation before the extreme value, which means that the increase of *Fintech* can mitigate the negative relationship between the government's environmental attention and green innovation in the short term.

In columns (4) to (6), we added the interaction term *Fintech*×*GEA*², and the results show that the regression coefficients of the interaction terms are significantly positive at the 10% level at least, indicating that after *GEA* reaches its extreme value, the positive relationship between government's

environmental attention and green innovation is enhanced by the increase of financial technology. The abovementioned results are consistent with hypothesis H3.

It should be noted that the moderating effect of *Fintech* on the sample of non-heavy polluting firms is not significant, which may be due to the development of *Fintech* improving the precision and effectiveness of green capital, alleviating resource mismatch (Tian et al., 2017), and providing financial support for heavy polluting firms which urgent to pursuit green innovation. Therefore, *Fintech* does not significantly increase the positive effect of the government's environmental attention on green innovation in non-heavy polluting firms. The hypothesis H3 is only proved in heavy-polluting firms, and the regression results for non-heavy-polluting firms are not reported here due to space constraints.

5.3 Heterogeneity effect

In the heterogeneity test, we further divided the firms into state-owned and non-state-owned groups according to the nature of equity. There are significant differences between state-owned and non-state-owned firms in terms of resource access, response to government policies, financing capacity, and relationship with the government (Zhang et al., 2022). We focused on whether the nature of equity affects the relationship between the government's environmental attention and green innovation. Table 4 reports the regression results of the government's environmental attention (*GEA*) on

TABLE 4 Heterogeneous effect test.

	Heavy-polluting firms		Non-heavy-polluting firms	
	(1)	(2)	(3)	(4)
	State-owned	Non-state-owned	State-owned	Non-state-owned
GEA	−10.680*	−2.653	−0.011	0.684***
	(6.189)	(2.624)	(0.341)	(0.196)
GEA ²	14.703*	3.086	0.002	−0.655
	(7.836)	(3.229)	(0.436)	(0.230)
_cons	10.397	−0.335	0.724	−0.075
	(22.283)	(5.327)	(0.564)	(0.364)
Control	Yes	Yes	Yes	Yes
Year, industry, and city	Yes	Yes	Yes	Yes
N	2,045	2,875	4,549	8,930
Adj.R2	0.017	0.012	0.058	0.059

the total green innovation (*GITotal*) of heavy polluters and non-heavy polluters, respectively.

The regression results are reported in columns (1) to (2) for the grouping of heavy polluters by the nature of equity. The results show that the coefficients of *GEA* and *GEA*² are significantly negative and positive, respectively, in the group of state-owned firms, but the coefficient of *GEA* is not significant for non-state-owned firms. One possible explanation is that state-owned firms reflect government regulations more effectively and enforce the regulations more strictly than non-state-owned, and state-owned firms generally have more obvious economies of scale and bear a stronger risk of innovation failure than non-state owned. Hence, the effect of the government's environmental attention on green innovation in state-owned firms is more significant in the grouping of heavy polluters.

Columns (3) to (4) report the regression results for non-heavy polluting firms by the nature of equity, the results show that the coefficient of *GEA* is significantly positive in the group of non-state firms, but the coefficient of *GEA* is not significant for state-owned firms. Since green innovation is not an inevitable choice for non-heavy-polluting firms and non-state firms face stronger financing constraints, therefore, with the increase in government's environmental attention, non-state-owned firms are more motivated to conduct green innovation for the signal of government recognition to receive government subsidies, tax rebates, and other government resources (Feldman and Kelley, 2006; Kleer, 2010). Hence, the government's environmental attention has a more significant impact on green innovation in non-state firms for non-heavy-polluting firms.

5.4 Mechanism

5.4.1 Channel of "crowding-out effect"

According to the previous theoretical analysis, the "crowding-out effect" and the "resource compensation effect" are the two main channels for the government's environmental attention to affect green innovation. The rise in the government's environmental attention increases the production costs and the associated costs of sewage to control pollution, which in turn decreases crowding-out investment in green innovation. Herein, we use the environmental related expenses to measure the "crowding-out effect." The variable *fees* in table 5 are the total environmental related expenses such as sewage charges, cleaning fees, and environmental protection inputs of the enterprise are taken as logarithms (Lu et al., 2019). Table 5 reports the regression results of the environmental related expenses as a mediating variable for heavy polluting firms and non-heavy polluting firms, respectively.

Columns (1) to (3) report the regression results for the group of heavy polluting firms. The result shows that the coefficient of *GEA* in column (2) is 2.062 with a significant positive sign, which means that the rise in the government's environmental attention significantly increases environmental related expenses. The coefficient of *fee* in column (3) is −0.192, which is significant at the 1% level, indicating that the rise in the government's environmental attention significantly increases the environmental related expenses of heavy polluters, which in turn crowds out innovation inputs and inhibits green innovation. Since the regression coefficients of *GEA* and *GEA*² are not significant, the financing constraint plays a full mediating effect. Columns (4) to (6) report the regression

TABLE 5 Mechanism of the environmental related expenses.

	Heavy-polluting firms			Non-heavy-polluting firms		
	(1)	(2)	(3)	(4)	(5)	(6)
	<i>GITotal</i>	<i>Fee</i>	<i>GITotal</i>	<i>GITotal</i>	<i>Fee</i>	<i>GITotal</i>
<i>GEA</i>	−4.372* (2.441)	2.062** (0.995)	−0.823 (2.189)	0.333** (0.135)	1.337 (1.371)	−0.081 (0.315)
<i>GEA</i> ²	6.301* (3.229)	−1.870 (1.215)	1.194 (2.587)	−0.310* (0.165)	−0.895 (1.668)	0.137 (0.389)
<i>Fee</i>			−0.192*** (0.050)			−0.002 (0.005)
<i>_cons</i>	−1.930 (5.028)	−7.910*** (1.989)	−0.503 (4.392)	0.052 (0.266)	−5.960** (2.659)	−0.210 (0.763)
<i>Control</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year, industry, and city</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	1840	1840	1840	1993	1993	1993
<i>Adj.R</i> ²	0.009	0.546	0.086	0.039	0.394	0.132

TABLE 6 Mechanism of the environmental subsidies.

	Heavy-polluting firms			Non-heavy-polluting firms		
	(1)	(2)	(3)	(4)	(5)	(6)
	<i>GITotal</i>	<i>Sub</i>	<i>GITotal</i>	<i>GITotal</i>	<i>Sub</i>	<i>GITotal</i>
<i>GEA</i>	−4.449* (2.490)	0.364* (1.105)	−0.793 (1.183)	0.125** (0.050)	0.544* (0.350)	0.183 (0.136)
<i>GEA</i> ²	6.476* (3.330)	−0.775 (1.373)	1.078 (1.320)	−0.394* (0.219)	1.253 (1.632)	−0.070 (0.583)
<i>Sub</i>			0.026 (0.028)			0.048*** (0.009)
<i>_cons</i>	2.558 (8.578)	14.937*** (0.323)	−1.418 (2.318)	0.143 (0.297)	12.933*** (0.264)	−2.104** (0.846)
<i>Control</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year, industry, and city</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	2,204	2,204	2,204	3,096	3,096	3,096
<i>Adj.R</i> ²	0.007	0.352	0.036	0.056	0.143	0.192

results for the sample of non-heavy polluters. We find that the increase in the government's environmental attention does not significantly affect environmental related expenses for non-heavy polluters. Therefore, the environmental related expenses are not the mechanism of influence between the government's environmental attention and the green innovation of non-heavy-polluting firms, which is also consistent with the previous theory.

5.4.2 Channel of "resource compensation effect"

The rise of the government's environmental attention increases the government's financial investment in environmental protection, which has a "resource compensation effect" on firms' green innovation and thus promotes green innovation. We use the logarithm of the number of environmental subsidies to measure the government's "resource compensation effect" (Yang et al., 2017). Table 6 reports the results of the test of environmental

TABLE 7 Estimation results for the 2SLS.

	(1)	(2)
	Heavy-polluting firms	Non-heavy-polluting firms
<i>GEA</i>	−1.065* (0.668)	3.277** (1.424)
<i>GEA</i> ²	1.409* (0.829)	−4.535 (2.040)
<i>Size</i>	0.171*** (0.014)	−0.011* (0.006)
<i>Age</i>	−0.009*** (0.002)	0.001 (0.001)
<i>Lev</i>	−0.239*** (0.060)	−0.033 (0.030)
<i>Roa</i>	−0.209 (0.176)	0.097 (0.085)
<i>Growth</i>	−0.036** (0.016)	0.010 (0.008)
<i>Cashflow</i>	0.458*** (0.131)	−0.098 (0.069)
<i>TobinQ</i>	0.028*** (0.007)	−0.004 (0.004)
<i>Indep</i>	0.131 (0.152)	0.013 (0.094)
<i>Lngdp</i>	0.035*** (0.009)	0.015 (0.027)
<i>_cons</i>	−3.577*** (0.349)	−0.354 (0.386)
<i>Year, industry, and city</i>	Yes	Yes
<i>N</i>	4,920	13,479
<i>Adj.R</i> ²	0.124	0.030

subsidies as mediating variables for heavy polluters and non-heavy polluters, respectively.

Columns (1) to (3) report the regression results for the group of heavy polluting firms. The result shows that the coefficient of *GEA* in column (2) is 0.364 with a significant positive sign, indicating that the increase in the government's environmental attention significantly increases the environmental subsidies of heavy polluting firms. The results of *GEA* and *Sub* in column (3), however, are not significant, indicating that the increase in environmental subsidies is not an effective mediating variable for the increase of green innovation in heavy polluting firms. The reason is that government environmental subsidies make the heavy polluting firms financially dependent, and the subsidies are more likely to be used to maintain survival rather than innovation (Xu and Li, 2019); therefore, environmental subsidies cannot significantly increase the green innovation of the heavy polluting firms.

Columns (4) to (6) report the regression results of the non-heavy polluters. In column (5), we find that the rise of the

government's environmental attention significantly increases environmental subsidies with a coefficient of 0.544. In column (6), environmental subsidies have a significant positive effect on green innovation, which means that the government's environmental attention can improve environmental subsidies which causes the increase of green innovation in non-heavy-polluting firms. Since the results of *GEA* are not significant, environmental subsidies play a full mediating effect, which is consistent with the theoretical derivation described earlier in this article.

5.5 Robustness test

5.5.1 Endogeneity problem

Although the benchmarking regression verifies our previous hypothesis, further research shows that there may be a causal endogeneity between the government's environmental attention and green innovation. When local firms have more green

TABLE 8 Estimation results for alternative control variable.

	Heavy-polluting firms		Non-heavy-polluting firms	
	(1)	(2)	(3)	(4)
<i>GEA</i>	−8.331** (3.540)	−8.585** (3.582)	0.423** (0.049)	0.433** (0.170)
<i>GEA</i> ²	10.909** (4.678)	11.272** (4.761)	−0.429* (0.198)	−0.451 (0.203)
<i>Lngdp</i>	0.856 (0.672)	0.819 (0.688)	0.039 (0.027)	0.039 (0.027)
<i>TE</i>	−0.089 (0.348)	−0.043 (0.354)	−0.047** (0.018)	−0.049*** (0.019)
<i>FD</i>	2.798 (2.466)	2.959 (2.534)	−0.150* (0.083)	−0.163* (0.086)
<i>Open</i>	−0.157 (0.282)	−0.162 (0.287)	−0.010 (0.009)	−0.008 (0.009)
<i>School</i>	0.827* (0.452)	0.698* (0.403)	0.039 (0.043)	0.044 (0.044)
<i>Size</i>		−0.756 (0.608)		−0.011* (0.006)
<i>Age</i>		0.012 (0.029)		0.001 (0.001)
<i>Lev</i>		2.417 (2.204)		−0.032 (0.030)
<i>Roa</i>		6.082 (4.464)		0.087 (0.085)
<i>Growth</i>		−0.211 (0.228)		0.011 (0.008)
<i>Cashflow</i>		−2.411 (1.880)		−0.104 (0.069)
<i>TobinQ</i>		−0.386 (0.238)		−0.004 (0.004)
<i>Indep</i>		1.512 (4.088)		−0.001 (0.093)
<i>_cons</i>	−12.451 (8.041)	3.935 (10.776)	0.363 (0.385)	0.595 (0.416)
<i>Control</i>	Yes	Yes	Yes	Yes
<i>Year, industry, and city</i>	Yes	Yes	Yes	Yes
<i>N</i>	4,989	4,869	13,715	13,382
<i>Adj.R</i> ²	0.007	0.010	0.055	0.057

innovation achievements, the officers may emphasize environmental related results in government work reports to highlight the government's performance, which results in higher government environmental attention.

To solve the endogeneity problem, we use the 2SLS instrumental variables approach for further testing. We choose the one-period lagged government's environmental attention primary term *L.GEA* and the one-period lagged government environmental attention secondary term *L.GEA*² as the

instrumental variables for *GEA* and *GEA*², which is a common practice since the endogenous variables with one lag period can meet the correlation assumption and the exogenous assumption of effective instrumental variables (Huang et al., 2022). The first-stage regression results also confirm the significant positive correlation between *L.GEA*² and *GEA*² as well as *L.GEA* and *GEA*.

Table 7 mainly reports the second-stage regression results in the 2SLS regression of government environmental attention

TABLE 9 Estimation results for excluding favorable environment cities.

	(1)	(2)
	Heavy-polluting firms	Non-heavy-polluting firms
<i>GEA</i>	−0.314** (3.602)	0.423** (0.188)
<i>GEA</i> ²	0.450** (4.985)	−0.394 (0.219)
<i>_cons</i>	8.684 (12.538)	0.337 (0.317)
<i>Control</i>	Yes	Yes
<i>Year, industry, and city</i>	Yes	Yes
<i>N</i>	4,370	10,868
<i>Adj.R</i> ²	0.010	0.053

(*GEA*) and green innovation (*GITotal*) for heavy polluters and non-heavy polluters, respectively. We notice that after controlling for endogeneity, the results of the *GEA* and *GEA*² of heavy polluters still significantly support the hypothesis of a U-shaped curve, but the coefficient decreases to 1.065, and the significance drops to 10%. As for the non-heavy polluters, the regression coefficient of *GEA* is still significantly positive, and the coefficient increases to 3.277. The coefficient of *GEA*² is still negative but not statistically significant. Therefore, after controlling for endogeneity, the regression results still support the hypothesis of this article.

5.5.2 Alternative control variable

In the robustness test, we try to replace and add control variables. Most of the existing literature on corporate green innovation controls for city-level macroeconomic variables and the control variables selected in this article are mainly corporate financial data. Therefore, to further test the robustness of the regression results, we chose to replace the control variables with macro control variables as follows (Zhu et al., 2022): (1) the level of science and technology expenditure (*TE*), measured by the logarithm of the share of general public budget expenditure on science and technology; fiscal decentralization (*FD*), the logarithm of the ratio of fiscal revenues to fiscal expenditures; regional openness (*Open*), measured by the logarithm of the actual amount of foreign capital used in the region; the number of higher education institutions (*schools*), the logarithm of the number of general higher education institutions in the city. Table 8 reports the regression results of government environmental attention (*GEA*) and green innovation (*GITotal*) for heavy and non-heavy polluters after replacing or adding macro control variables. The coefficients' symbols and significance of the test are generally consistent with the results in the benchmarking regression, which further supports our previous conclusions.

5.5.3 Sample excluding favorable environment cities

In a further robustness test, we exclude samples that are located in the cities of Qingdao, Yantai, Lishui, Taizhou, Fuzhou, Xiamen, Shenzhen, Zhuhai, Huizhou, Zhongshan, Guiyang, Haikou, and Kunming, which have a relatively favorable environment (Zhu et al., 2022), because cities with the relatively favorable environment may have less pressure on environmental governance. Table 9 shows the regression results of government environmental attention (*GEA*) and green innovation (*GITotal*) for heavy polluters and non-heavy polluters after removing the samples. The coefficients' symbols and significance of the robustness test are generally consistent with the results in the benchmarking regression, which further supports our previous conclusions.

6 Conclusion and policy recommendations

6.1 Conclusion

This article examines the influence and differential influence mechanism of the government's environmental attention on green innovation in heavy-polluting and non-heavy-polluting firms, using data of Chinese A-shares listed companies in Shanghai and Shenzhen stock exchanges from 2011 to 2019. It also investigates the moderating effect of financial technology on the relationship between government environmental attention and green innovation. The following are the conclusions:

- (1) There is a distinction between heavy polluting and non-heavy polluting firms concerning the effect of the government's environmental attention on green

innovation. Using OLS regression models, the 2SLS instrumental method, and other robustness tests, we demonstrate that as the government's environmental attention shifts from weak to strong, its impact on heavy polluters' green innovation will shift from negative to positive. "U"-shape is the relationship between the government's environmental attention and green innovation. In the meantime, the government's environmental attention positively impacts the green innovation of non-heavy polluting firms, with a greater impact on green invention patents than on green utility model patents.

- (2) As for the mediating effects of Fintech, the regression results indicate that an increase in Fintech can mitigate the negative relationship of heavy polluters between the government's environmental attention and green innovation in the short term. Moreover, after the government's environmental attention reaches its extreme value, an increase in Fintech strengthens the positive relationship between the government's environmental attention and green innovation. However, Fintech's moderating effect on the non-heavy-polluting group is insignificant.
- (3) According to the heterogeneity test, the effect of the government's environmental attention on green innovation in state-owned firms is greater than in non-state-owned firms in the grouping of heavy polluters. In contrast, the government's environmental attention significantly impacts green innovation in non-state firms by grouping non-heavy polluters.
- (4) The "crowding-out effect" channel plays a mediating role in heavy polluters. Results indicate that an increase in the government's environmental attention significantly increases environmental related expenses, which, in turn, crowds out innovation inputs and impedes green innovation among heavy polluters. On the other hand, the "resource compensation effect" channels have a moderating effect on non-heavy polluters since the government's environmental attention can increase environmental subsidies, which in turn increases green innovation in non-heavy-polluting firms.

6.2 Policy recommendations

Based on our findings, we propose the following recommendations and wish to provide developing or transitioning nations and regions with experience. To improve the green innovation of firms, the government must first increase its attention to environmental protection in a sustainable manner. Before the inflection point, they should pay attention to the negative impact on heavy polluters and make efforts to alleviate their financing constraints. If the government's environmental attention fluctuates too much over a short period, it may threaten the viability of green innovation.

Second, enhancing the government's environmental attention is advantageous for the green innovation of non-heavy polluting firms, which are also crucial R&D firms for green innovation. Therefore, the government should pay greater attention to the green innovation of non-heavy-polluting firms and implement continuous stimulation policies to sustain the innovation zeal of non-heavy-polluting firms. Lastly, the government should actively improve the level of regional financial technology, which is conducive to enhancing the allocation efficiency of funds, reducing the inhibiting effect of the government's environmental attention enhancement on the green innovation of heavy pollution firms in the short term, and enhancing the promotion effect on green innovation in the long term.

Data availability statement

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

Author contributions

Conceptualization, JC and QL; methodology, JC; software, JC; formal analysis: JC and QL; writing—original draft preparation, JC; writing—review and editing, QL and XW; visualization, XW.

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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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Does the carbon trading mechanism affect social and environmental benefits of the retailer-led supply chain: Strategic decisions of emissions reduction and promotion

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Governments, enterprises, and customers have become more concerned about environmental protection. Following the world's largest carbon trading market (EU ETS), China has also implemented a market-based carbon trading mechanism (CAT) to reduce CO₂. Simultaneously, customers have low-carbon preferences for environmental products. Thus, the enterprises' strategic decisions and collaboration modes have changed. This article develops the Stackelberg game model to explore the impacts of CAT and customers' low-carbon preference on the carbon emission reduction and promotion strategies in a retailer-led supply chain (such as RT-Mart, Walmart, Amazon, etc.). In this model, the retailer decides whether to promote environmentally safe products and the manufacturer decides whether to reduce CO₂. We find that carbon trading market price and customers' low-carbon preference are key factors influencing the retail price, total carbon emissions, and social welfare. Interestingly, there is not always a positive correlation between customers' low-carbon preference and social welfare. To achieve Pareto improvement of social welfare, manufacturers and retailers require co-optimization. Theoretically, our research enriches the research streams of the CAT policy and socially responsible operations of the supply chain. Moreover, managerial insights are provided for retailer-led supply chain stakeholders and emission reduction regulators, which contribute to enhancing the social and environmental benefits of the supply chains.

KEYWORDS

carbon trading, emissions reduction, consumers' low-carbon preferences, stackelberg game, promotional efforts

Introduction

Carbon dioxide, methane, ozone, and other greenhouse gasses (GHG) from industrial production processes mainly cause climate change. Among them, carbon dioxide accounted for the highest proportion of 65% (Solomon et al., 2009). Governments and enterprises are becoming more concerned about environmental protection (Fang et al., 2021). To achieve its carbon peak and carbon neutrality targets, China has implemented policies, legislations, and supporting measures for peaking CO₂ emissions in core areas and key industries, and map paths (such as the “1 + N” policy framework) to achieve carbon peaking and carbon neutrality goals (Z. Sun et al., 2022). Following the world’s largest carbon trading market (EU ETS), China has also implemented a market-based carbon trading mechanism (CAT) to reduce carbon emissions. CAT is a market-based mechanism that allows carbon credits to be traded freely as a commodity. At the beginning of each accounting year, the government allocates free carbon quotas (called emissions cap) to an enterprise with high carbon emissions. The cap is always the hardest challenge in CAT. If the enterprise emits a smaller amount of CO₂ emissions than the emissions cap, it can gain additional revenue by selling surplus carbon quotas; otherwise, to avoid high fines, it has to go to the carbon trading market to buy carbon quotas (Benjaafar, Li, and Daskin 2013). Since 2011, China has established Beijing, Shanghai, Guangdong, and five other carbon trading systems. That means that CAT, which could have an impact on the enterprises’ strategic decisions and collaboration modes, has created a new mechanism of the costs and returns account for enterprises.

Another factor that contributes to strategic decisions in a retailer-led supply chain is the customers’ environmental preferences. In recent years, customers have become more concerned about protecting the environment and are willing to pay more for low-carbon products. Low-carbon products (e.g. natural bamboo and wood products, solar energy products, electronic signatures, and inverter air conditioners) refer to products that can save energy and reduce GHG emissions. “Carbon labels” or other channels can provide information on the emission-reduction level for consumers. The 2021 China Sustainable Consumption Report said that over 70% of consumers believe that low-carbon consumption can motivate the achievement of the “30-60” carbon peaking and carbon neutrality goals.

As mentioned previously, a manufacturer may be incentivized by CAT and customers’ environmental preferences to invest in carbon reduction technologies (e.g. IRWIN’s Carbon Cure CO₂ recovery technology) and projects such as Carbon Sequestration Project (Sun et al., 2020). In 2020, Alibaba conducts clean energy power trading. From January to September 2021, Alibaba traded 224 million kWh of green electricity. From 2018 to September 2021, Alibaba’s Zhangbei

Data Center has traded about 600 million kWh of new energy electricity and reduced carbon emissions by 523,000 tons. Meanwhile, powerful retailers (e.g. RT-Mart, Auchan, H&M, Amazon, Alibaba) have gradually more pricing power than manufacturers (Lou et al., 2020; Yuyan Wang et al., 2021), some retailer-led supply chains have occurred. These retailers become more socially responsible to protect the environment (Styles, Schoenberger, and Galvez-Martos 2012). They can install ventilation systems with heat recovery, build an eco-friendly distribution center, encourage customers to participate in environmental protection activities, and promote low-carbon products with carbon labeling by displaying them in preferential areas (Brunner et al., 2018). For instance, Walmart has established a low-carbon marketing team to carry out low-carbon public relations, and actively cooperate with the government, associations, and the media. Walmart has participated in the “Hundreds of Low-Carbon Demonstration Stores” organized by the Chain Store and Franchise Association in China. Walmart also held a 2-month long theme activity named “Focus on Climate Warming and Make the Earth Healthier”. Through low-carbon marketing, Walmart transmits a good low-carbon corporate image to its suppliers and customers.

However, each stakeholder is not concerned about the entire supply chain’s profits; they only act for their own maximized profits. When one enterprise makes efforts to reduce emissions or promote green/sustainable products, other companies will take a free ride to the benefit from the spillover that emerges (Gui et al., 2022). The one who invests in eco-friendly actions will feel unfair. Therefore, this contradiction can be alleviated by cooperation between the upstream and downstream stakeholders to reduce emissions.

Up to now, a thorough understanding of the impacts of CAT on its social and environmental benefits of a retailer-led supply chain and its implications to different stakeholders who are environmentally conscious is absent in the literature yet, especially in operations management (OM). To address this gap, we want to answer the following questions: 1) What are the strategic decisions of supply chain stakeholders under different scenarios considering the consumers’ low-carbon preference and CAT mechanism? 2) What effects do the market price of carbon credits, emission cap, consumers’ environmental behaviors, and other external parameters exert on the equilibrium solutions, total carbon emissions, and profits of the supply chain? 3) What management insights can governments and enterprises get?

We organize the rest of our article as follows: In the *Literature review* section, we review the relevant literature and identify our research gaps. In the *Model formulation* section, we describe the model formulations and derive the equilibrium solutions under each strategy combination of the retailer and the manufacturer who all make efforts to do socially responsible operations. In the *The results analysis* section, we theoretically analyze the equilibrium

solutions under different modes. In the *Modeling calibration and discussions* section, we conduct a numerical study and explore more managerial insights. All the proofs are postponed to Appendix A.

Literature review

Considering the CAT mechanism and consumers' environmental preference for low-carbon producing and selling, this article drives the strategic decisions for the manufacturer and retailer. There are three streams of literature related to this study: 1) sustainable supply chain management, 2) socially responsible operations of the supply chain, and 3) consumers' buying behavior based on environmental preference.

The first stream of literature related to this study is sustainable supply chain management. We refer readers to Goulder and Schen (2013), Barbosa-Povoa et al. (2018), Koberg and Longoni (2019), and Lu et al. (2022) for comprehensive reviews. Fang et al. (2021) applied the Differences in Differences (DID) method to find that government environmental regulations have a positive impact on corporate green innovation. To increase the benefits of an integrated forward/reverse logistics network and maximize the score of green design and quality indicators, Porkar et al. (2020) developed bi-objective non-linear programming. Zakeri et al. (2015) examined the supply chain performance under carbon taxes and carbon emissions trading by an analytical supply chain planning model. The results showed that the carbon trading scheme was better. Yang et al. (2020) compared the total emission reduction and operational decisions under the grandfathering and benchmarking rules for the allocation of carbon quotas. They found that the emission reduction under the grandfathering rule was greater. Above all, we concluded that these existing studies have mainly researched the impacts of macroeconomic regulations that control carbon emissions on the supply chain performance, ignoring the collaboration mode among supply chain stakeholders, especially in a socially responsible operations management.

Another stream of literature closely related to our study is the socially responsible operations of the supply chain. Some latest literature studies have investigated the low-carbon scenario or carbon-neutral potential of building operations. Xiang et al. (2022) used the decomposing structural decomposition method to assess the decarbonization progress of commercial building operations taking China and the United States (U.S.) as examples. S. Zhang et al. (2022) illustrated the potential for progressive decarbonization of global commercial building operations to achieve carbon neutrality. However, these studies did not consider the CAT mechanism.

A new mechanism of the costs and returns account for enterprises has been created by CAT, which could have an

impact on the enterprises' operation strategies and cooperation modes with other companies (Ma et al., 2021). From the operational management point of view, Wang et al. (2019) studied the joint replenishment policy as well as the carbon trading behavior for a fresh food supply chain. They found that retailers' leader-follower structure could cause the least carbon emissions. Considering environment protection, Taleizadeh et al. (2022) developed an EOQ model based on partial trade credit combined with partial back-ordering. In this article, demand is affected by selling price and carbon emissions per unit of product. Based on the decision theory, Saunders et al. (2020) determined the optimal level of sustainability for bidding suppliers considering the buyers' environmental preferences. Min Wang et al. (2021) optimized the operational decisions of a transnational manufacturer under different carbon trading mechanisms implemented in two countries. Xu and Wang (2018) indicated that decentralized decision-making in CLSC could cause a double-marginal effect and affect the operating efficiency of the supply chain. Yuyan Wang et al. (2021) constructed three decision-making models to compare the decisions and benefits of the stakeholders. They proposed a cost-sharing contract with an altruistic preference to coordinate the retailer-led low-carbon supply chain, and found that retailers needed to share more than 1/2 of the carbon emissions cost. Based on the carbon trading mechanism, Mondal and Giri (2021) developed centralized, decentralized, retailer-led revenue sharing, and bargaining revenue sharing models. In addition, they assumed that the manufacturer, retailer, and consumers are all environmentally conscious. The results demonstrated that retailer-led revenue sharing could coordinate the supply chain and improve benefits for both stakeholders. However, they did not consider the retailer's environmental behavior, such as promoting low-carbon products by advertising or displaying them in the preferential area.

Recently, customers have become more concerned about protecting the environment and are willing to pay more for low-carbon products (Du et al., 2015; Dardanoni and Guerriero 2021). To solve the problem of carbon emissions transfer and reduction among supply chain stakeholders, Sun et al. (2020) constructed a Stackelberg differential game model with considerations of emissions reduction technology lag time and customers' environmental preferences. Tong and Du (2019) developed an actual evolutionary game process to examine the evolution of the behaviors of powerful retailers and manufacturers with consideration of CAT and customers' low-carbon preferences.

The work that is most related to ours is that of Xia et al. (2018), who indicated that customers' low-carbon preferences motivated supply chain members to make efforts to reduce carbon emissions and promote low-carbon products under the CAT system. Our work differs from that of Xia et al. (2018) in two aspects as follows. First, Xia et al. (2018) suppressed the influence of wholesale price and retailer price. In this work, we optimize both wholesale price and retailer price. Second, Xia et al. (2018) analyzed the farms'

TABLE 1 The contributions of our research.

Studies	CAT	Retailer-Led Supply Chain	Retail Price		Collaboration Mode	Demand is Sensitive to		
			Exogenous	Endogenous		Carbon Emissions	Promotion Level	Customers' Low-Carbon Preference
Saunders et al. (2020)	—	—	—	*	—	*	—	—
Xu and Wang (2018)	—	—	—	*	*	*	—	*
Yuyan Wang et al. (2021)	—	*	—	*	*	*	—	*
Zakeri et al. (2015)	*	—	*	—	—	—	—	—
Wang et al. (2019)	*	—	—	*	—	—	—	—
Min Wang et al. (2021)	*	—	*	—	*	—	—	—
Taleizadeh et al. (2022)	*	—	*	*	—	*	—	—
Sun et al. (2020)	*	—	*	—	*	*	—	*
Tong and Du (2019)	*	*	—	*	—	*	*	*
Mondal and Giri (2021)	*	*	—	*	*	*	—	*
Xia et al. (2018)	*	*	*	—	—	*	*	*
This study	*	*	—	*	*	*	*	*

environmental behavior from the perspective of coordinating the supply chain, and thus did not take into account the collaboration modes among supply chain stakeholders. From the perspective of micro-games, we characterized the farms' equilibrium strategic decisions under five scenarios.

For the convenience of the readers, a quick overview of the closely relevant previous research articles has been provided in comparative Table 1. From this table, most mentioned articles have failed to take carbon emission issues of the retailer-led supply chain structure into account. Also, most articles on carbon emissions have failed to consider the collaboration modes and the environmental preferences of the manufacturer, retailer, and consumers simultaneously in real-life situations. Therefore, our research enriches the research streams mentioned previously. That is, to address these gaps, we developed the Stackelberg game model to explore the impacts of CAT and customers' low-carbon preference on the carbon emissions reduction and promotion strategies in a retailer-led supply chain.

Model formulation

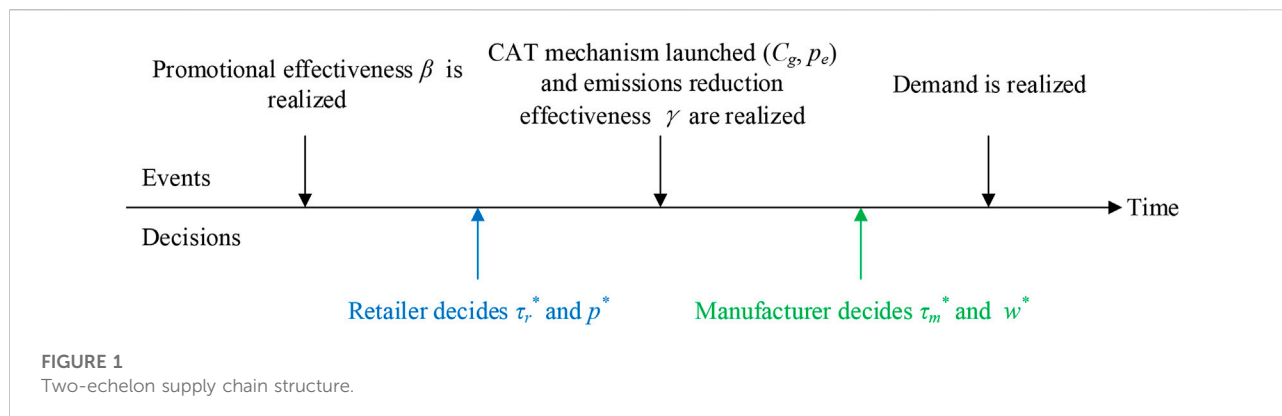
Model description

In this section, considering the CAT mechanism and customers' low-carbon preferences, we develop a Stackelberg game model to

identify the optimal decisions for the manufacturer and retailer who are perfectly rational and make economic profits. In a retailer-led supply chain, the manufacturer responds to customers' environmental preferences by introducing low-carbon products to meet the demand. It sells ordinary products or low-carbon products to the retailer. The retailer sells these products to the customers. The timeline of the events is as follows (see Figure 1).

As depicted in Figure 1,

- 1) the effectiveness of promoting low-carbon products β can be realized by retailer's market survey or forecasting. Based on β , the retailer simultaneously and individually decides whether to invest in promoting low-carbon products (P) or not invest in promotion (NP), the promotional effort level τ_r , and low-carbon products' retail price p . The promotion cost coefficient can be denoted as h_r .
- 2) Based on the baseline method, the manufacturer can be allocated free carbon quotas C_g by the government. The initial carbon emissions per unit of product are e_m . In particular, carbon credits can only be bought/sold in one production period at market price p_e . The carbon trading price is only determined by the carbon market. Particularly, we assume that the technology of carbon emissions reduction will not change significantly in a short period because of the long investment cycle. The manufacturer's market survey can realize the effectiveness of carbon emissions reduction γ .



- 3) According to the retailer's decisions and information about CAT, the manufacturer acts as a follower who simultaneously and individually decides whether to invest in reducing carbon emissions (R) or not reducing carbon emissions (NR), the emissions reduction level τ_m , and the products' wholesale price w . Emissions reduction investment coefficient can be denoted as h_m . The production cost per unit of the product is fixed and environmental improvement has an increasing marginal cost.
- 4) Each consumer chooses to buy the products that maximize their utility. We assume the fixed potential market demand is a . The price elasticity of demand is b .

The objectives of the retailer and manufacturer are to maximize their profits. In the following, we denote the equilibrium values by an asterisk "*". When supply chain stakeholders make decentralized decisions, four strategy combinations are proposed: NN (NP, NR), PN (P, NR), NR (NP, R), and PR (PS, R). We construct the cooperation mode: SC mode when supply chain stakeholders make centralized decisions.

Under centralized decision-making (SC mode), the manufacturer adopts a carbon emissions reduction strategy while the retailer adopts a promotion strategy. In this cooperation model, the demand D is affected by the retail price, emissions reduction level, and promotion level. The demand function is given by Equation (1).

$$D = a - bp + \gamma\tau_m + \beta\tau_r \quad (1)$$

The overall profit functions for the supply chain are provided as follows:

$$\pi_{r,m}^{SC} = (p - c_m - c_r)q - [e_m(1 - \tau_m)q - C_g]p_e - \frac{1}{2}h_m\tau_m^2 - \frac{1}{2}h_r\tau_r^2 \quad (2)$$

where c_r denotes the retail cost, and c_m denotes the production costs. The production cost per unit of the product is fixed and the investment costs of emissions reduction and promotion will

change. It is well known that the improvement of environmental and promotional levels has an increasing marginal cost. Thus, the costs of promotion and carbon emissions reduction follow a quadratic function, respectively, based on the results from Laffont and Tirole (1993) and Savaskan and Van Wassenhove (2006), i.e. $\frac{1}{2}h_r\tau_r^2$ and $\frac{1}{2}h_m\tau_m^2$. $\pi_{r,m}^{SC}$ denotes the profits of the entire supply chain.

Optimal solutions

When the manufacturer and retailer make decentralized decisions, the optimal solutions for the manufacturer and retailer in each combination strategy are present in our previous research (Tong and Mu, 2019). To proceed with the analysis, we make the following assumptions:

Assumption. $2bh_r - \beta^2 > \frac{h_r}{h_m}(\gamma + be_m p_e)^2$

This assumption shows the relationship between the various system parameters. It indicates that consumers are reasonably price-sensitive. In particular, the price elasticity of demand, b , needs to be limited. This is because, if the consumers are highly price-sensitive, the players will achieve price-war equilibrium. This assumption also shows that the retailer is promotion cost-sensitive and the manufacturer is reduction cost-sensitive. Take the manufacturer as an example, the assumption implies that if a manufacturer decides to reduce carbon emissions with his maximum effort, he can substantially improve the environmental quality of his products. That is, each stakeholder will set his level of emissions reduction/promotional efforts at the marginal cost. Based on Equation (2) established for the supply chain, the optimal solutions are shown in Theorem 1.

Theorem 1. There exists a unique optimal solution to the SC mode. The optimal promotional effort level, the emissions reduction level, production quantity, and retail price and production are as follows:

Proof. The third-order Hessian matrix for Equation (2) is

$$H = \begin{bmatrix} -2b & \beta & \gamma - bp_e e_m \\ \beta & -h_r & \beta e_m p_e \\ \gamma - bp_e e_m & \beta p_e e_m & 2\gamma p_e e_m - h_m \end{bmatrix}, \text{ where the value of}$$

the first-order determinant is $H_1 = -2b$. According to the assumption, the value of the second-order determinant satisfies $H_2 > 0$, and the third-order determinant satisfies $H_3 < 0$, that is, when $2bh_m - (\gamma + be_m p_e)^2 > \frac{\beta^2 h_m}{h_r} > 0$, $\pi_{r,m}^{SC}$ is a joint concave function for p, τ_r, τ_m and has a maximum value in the range. Letting the first-order partial derivative of the profit function be zero, the unique optimal decisions can be solved.

$$(\tau_r^{SC})^* = \frac{\beta h_m [a - b(c_m + c_r + e_m p_e)]}{h_r [2bh_m - (\gamma + be_m p_e)^2] - \beta^2 h_m} \quad (3)$$

$$(\tau_m^{SC})^* = \frac{h_r (\gamma + bp_e e_m) [a - b(c_m + c_r + e_m p_e)]}{h_r [2bh_m - (\gamma + bp_e e_m)^2] - \beta^2 h_m} \quad (4)$$

$$(p^{SC})^* = \frac{h_r [a - b(c_m + c_r + e_m p_e)] [h_m - e_m p_e (\gamma + be_m p_e)]}{h_r [2bh_m - (\gamma + be_m p_e)^2] - \beta^2 h_m} + c_r + c_m + e_m p_e \quad (5)$$

$$(q^{SC})^* = \frac{bh_m h_r [a - b(c_m + c_r + e_m p_e)]}{h_r [2bh_m - (\gamma + bc_e e_m)^2] - \beta^2 h_m} \quad (6)$$

The profit of manufacturer and retailer is $(\pi_{r,m}^{SC})^* = \frac{h_r h_m [a - b(c_m + c_r + e_m p_e)]^2}{2[h_r [2bh_m - (\gamma + be_m p_e)^2] - \beta^2 h_m]} + C_g p_e$.

The results analysis

Comparison of emissions reduction levels

Proposition 1. The ratio of the emissions reduction level under the (P, R) strategy to that under the (N, R) strategy is greater than 1.

From Tong and Du (2019), we know that,

$$(\tau_m^{NR})^* = \frac{(\gamma + be_m p_e) [a - b(c_m + e_m p_e + c_r)]}{4bh_m - 2(\gamma + be_m p_e)^2}, \text{ and} \quad (7)$$

$$(\tau_r^{PR})^* = \frac{\beta h_m [a - b(c_m + e_m p_e + c_r)]}{2h_r [2bh_m - (\gamma + be_m p_e)^2] - \beta^2 h_m} \quad (8)$$

Let, $\Delta_1 = 2[2bh_m - (\gamma + be_m p_e)^2]$, $\Delta_2 = 2h_r [2bh_m - (\gamma + be_m p_e)^2] - \beta^2 h_m$.

Therefore,

$$\frac{(\tau_m^{PR})^*}{(\tau_m^{NR})^*} = \frac{2[2bh_m - (\gamma + be_m p_e)^2]}{2h_r [2bh_m - (\gamma + be_m p_e)^2] - \beta^2 h_m} = \frac{\Delta_1}{\Delta_2} = \frac{\Delta_2 + \frac{\beta^2 h_m}{h_r}}{\Delta_2} > 1 \quad (9)$$

Proposition 2. implies that, under the PR strategy, the emissions reduction level is twice as high as that of the NR strategy. It means that, although the retailer does not contribute to carbon emissions reduction and low-carbon product

promotion, they can benefit from the manufacturer's emission reduction as the manufacturer is a rational agent who is concerned about fairness. Compared with the PR strategy, the manufacturer has a lower willingness to reduce emissions under the NR strategy.

Comparison of profits

Proposition 3. The relationship between the profits of the retailer and the manufacturer under centralized decision-making and decentralized decision-making is: $(\pi_{r,m}^{SC})^* > (\pi_m^{PR})^* + (\pi_r^{PR})^*$.

If $2bh_m - (\gamma + be_m p_e)^2 > \frac{\beta^2 h_m}{h_r} > 0$, we know that $(\pi_r^{NN})^* = (\pi_r^{PN})^* < (\pi_r^{NR})^* < (\pi_r^{PR})^*$. It indicates that the manufacturer and the retailer earn the most profits in PR, followed by the NR strategy combination. We can get $\pi_m^{NN} + \pi_r^{NN} = \pi_m^{PN} + \pi_r^{PN} < \pi_m^{NR} + \pi_r^{NR} < \pi_m^{PR} + \pi_r^{PR}$, which means that when a retailer promotes low-carbon products and the manufacturer reduces emissions, the profits of the entire supply chain is significantly greater than others. It is easy to get $(\pi_{r,m}^{SC})^* > (\pi_m^{PR})^* + (\pi_r^{PR})^*$ as a different method.

If the manufacturer invests in reducing carbon emissions or the retailer adopts promotional strategies, it will help increase their profits and supply chain profits. The overall profit of the retailer and the manufacturer under centralized decision-making is higher than that under decentralized decision-making. It indicates that, when the retailer adopting a promotion strategy cooperates with the manufacturer adopting a carbon emissions reduction strategy, it is beneficial for increasing the profit of the supply chain.

Comparison of total carbon emissions

Proposition 3. The relationship between the carbon emissions per unit of a product under centralized decision-making and decentralized decision-making is $E^{NN} = E^{PN} > E^{NR} > E^{PR} > E^{SC}$.

We assume that carbon emissions per unit of product under each combination are $E^i, i = NN, PN, NR, PR, SC$. Under strategy NN and strategy PN, since the manufacturer does not invest in reducing carbon emissions, the decision sequence and final strategy of the manufacturer and the retailer are consistent, so the carbon emissions per unit of the product are the same, that is, $E^{NN} = E^{PN} = e_m$. Under strategy NR, when the manufacturer makes an effort to reduce carbon emissions, the emissions reduction level is τ_m^{NR} , and then the term $E^{NR} = e_m (1 - \tau_m^{NR})$ denotes the current carbon emissions per unit of the product. Similarly, under the PR strategy combination, the carbon emissions per unit of the product are $E^{PR} = e_m (1 - \tau_m^{PR})$ after the manufacturer takes measures to reduce carbon emissions. When the manufacturer and retailer make decisions together, the carbon emissions per unit of product are $E^{SC} = e_m (1 - \tau_m^{SC})$.

According to Proposition 1, we know $\tau_m^{NR} < \tau_m^{PR} < \tau_m^{SC}$, then we can get $E^{NR} > E^{PR} > E^{SC}$; above all, $E^{NN} = E^{PN} > E^{NR} > E^{PR} > E^{SC}$ can be obtained.

Proposition 4. The relationship between the production quantities under each strategy combination is: $(q^{NN})^* = (q^{PN})^* < (q^{NR})^* < (q^{PR})^*$.

According to Tong and Du (2019), we can rewrite the manufacturer's production quantity under each strategy combination as

$$(q^{NN})^* = (q^{PN})^* = \frac{a - b(c_m + e_m p_e + c_r)}{4} \quad (10)$$

$$(q^{NR})^* = \frac{bh_m[a - b(c_m + e_m p_e + c_r)]}{4bh_m - 2(\gamma + be_m p_e)^2} = \frac{a - b(c_m + e_m p_e + c_r)}{4 - \frac{2(\gamma + be_m p_e)^2}{bh_m}} \quad (11)$$

$$(q^{PR})^* = \frac{bh_r h_m [a - b(c_m + e_m p_e + c_r)]}{2h_r [2bh_m - (\gamma + be_m p_e)^2] - \beta^2 h_m} = \frac{[a - b(c_m + e_m p_e + c_r)]}{4 - \frac{2(\gamma + be_m p_e)^2}{bh_m} - \frac{\beta^2}{bh_r}}, \text{ and} \quad (12)$$

$$(q^{SC})^* = \frac{bh_m h_r [a - b(c_m + c_r + e_m p_e)]}{h_r [2bh_m - (\gamma + be_m p_e)^2] - \beta^2 h_m} \quad (13)$$

Since $\frac{2(\gamma + be_m p_e)^2}{bh_m} + \frac{\beta^2}{bh_r} > \frac{2(\gamma + be_m p_e)^2}{bh_m} > 0$, we can find $(q^{NN})^* = (q^{PN})^* < (q^{NR})^* < (q^{PR})^* < (q^{SC})^*$. Based on the aforementioned two properties, we know that when the manufacturer chooses to reduce carbon emissions or the retailer chooses to invest in promoting low-carbon products, the carbon emissions per unit of the product will decrease, but the production quantity will increase accordingly. When the retailer and the manufacturer fully cooperate, the carbon emissions per unit of the product are the lowest, but the production quantity is the highest. Then, no matter under what strategy combination is used, the relationship between the total carbon emissions of the supply chain cannot be determined. That is, companies seeking to maximize their benefits will cost the environment. Therefore, the trade-off between environmental protection and economic development is crucial.

The impacts of carbon credit market price on emissions reduction level

Proposition 5. The impacts of carbon credit market price on emissions reduction levels under strategy NR are summarized in this proposition.

1) If $h_m < \frac{(a+1)^2}{2}$, then $\frac{\partial(\tau_m^{NR})^*}{\partial p_e} > 0$, which indicates $(\tau_m^{NR})^*$ increases with the increase of p_e .

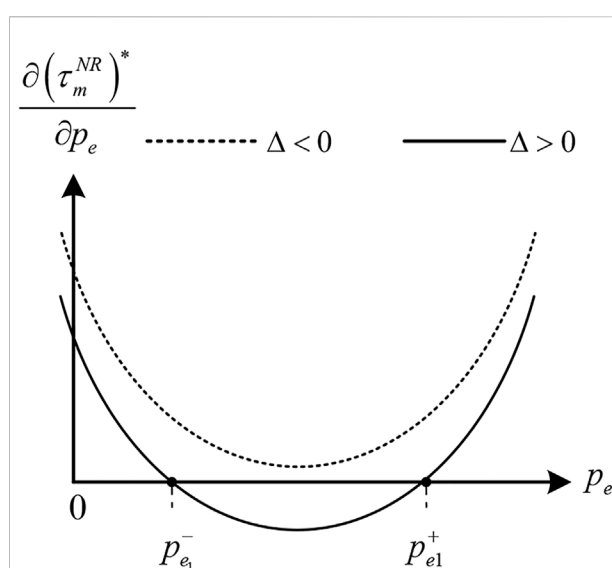


FIGURE 2
The first partial derivative of the emissions reduction level with respect to p_e under strategy NR.

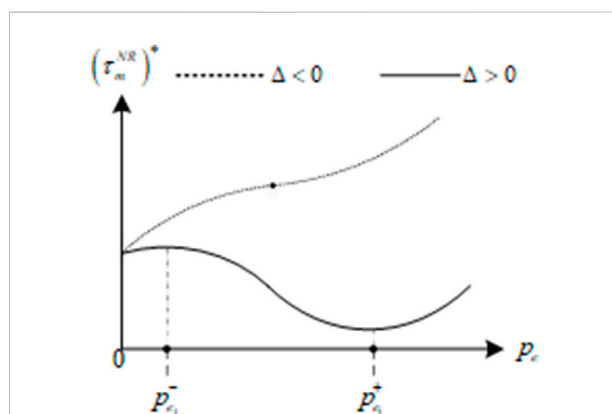


FIGURE 3
Emissions reduction level under strategy NR.

2) If $h_m > \frac{(a+1)^2}{2}$, then in the interval $(\frac{(2h_m - a - 1) - \sqrt{2h_m[2h_m - (a+1)^2]}}{a+1}, \frac{(2h_m - a - 1) + \sqrt{2h_m[2h_m - (a+1)^2]}}{a+1})$, we have $\frac{\partial(\tau_m^{NR})^*}{\partial p_e} < 0$ and in other intervals it is opposite.

See Appendix A for proof. We can easily find that $\frac{\partial(\tau_m^{NR})^*}{\partial p_e} > 0$, which means that $(\tau_m^{NR})^*$ increases with the increase of p_e . These results indicate that when the emissions reduction cost coefficient is relatively small, that is $h_m < \frac{(a+1)^2}{2}$, the manufacturer is likely to reduce carbon emissions easily. Then, with the increase of the

carbon allowances' market price, the emissions reduction level increases gradually. Subsequently, due to the diminishing marginal utility of carbon emissions reduction, the emissions reduction level slows down gradually to 0 (corresponds to the lowest point in the dashed line in Figure 2 and the turning point in the dashed line in Figure 3). However, when the market price of carbon credits continues to increase, the manufacturer will choose to make more efforts to reduce emissions to gain profit from selling surplus carbon quotas. Therefore, the emissions reduction level increases with the increase of carbon trading prices.

When $h_m > \frac{(a+1)^2}{2}$, then $\Delta = 8h_m[2h_m - (a+1)^2] > 0$. In the interval $(\frac{(2h_m-a-1)-\sqrt{2h_m[2h_m-(a+1)^2]}}{a+1}, \frac{(2h_m-a-1)+\sqrt{2h_m[2h_m-(a+1)^2]}}{a+1})$, we have $\frac{\partial(\tau_m^{PR})^*}{\partial p_e} < 0$ and in other intervals it is opposite (see the dotted line in Figure 2 and Figure 3).

If the value of the emissions reduction cost coefficient is relatively small, that is $h_m > \frac{(a+1)^2}{2}$, the manufacturer should invest more money in reducing carbon emissions to achieve a certain emissions reduction level. Under the carbon policies, the manufacturer chooses to reduce carbon emissions instead of buying carbon credits on the market; however, since the marginal utilities diminish, the emissions reduction level will maintain that maximum value even if the manufacturer tries to pay more money for the investment (see the corresponding vertex of p_{e1}^- in Figure 3).

When the emissions reduction hits a plateau, once the emissions reduction level attains the peak, the manufacturer will give up investing in reducing carbon emissions, which leads to a lower emissions reduction level. However, under the impact of increasing carbon trading prices and tight carbon policies, the manufacturer will want to gain more profit from carbon emissions reduction. Then, the emissions reduction level will decrease slowly (see the interval (p_{e1}^-, p_{e1}^+) in Figure 3). Subsequently, the optimal emissions reduction level increases with the increase in the carbon trading price.

As mentioned previously, the emissions reduction level varies with the price of carbon trading and different difficulties in reducing emissions. When the manufacturer can reduce emissions easily, the market price of carbon credits has a positive relation to the emissions reduction level. Initially, compared with the high emissions reduction cost coefficient situation, the reduction level increases more rapidly under the condition of the lower emissions reduction cost coefficient.

When the emissions reduction cost coefficient is higher, the manufacturer chooses to buy carbon allowances, which leads to the emissions reduction level increasing slowly and then has negative growth. Since the carbon trading costs increase with the increase of the carbon trading price, the manufacturer will choose to invest in reducing carbon emissions again to raise the emissions reduction level.

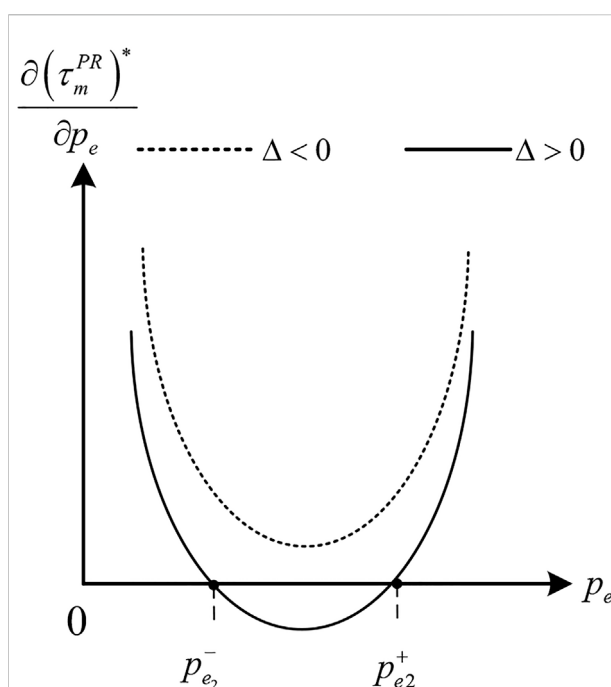


FIGURE 4
The first partial derivative of the emissions reduction level with respect to p_e under strategy PR.

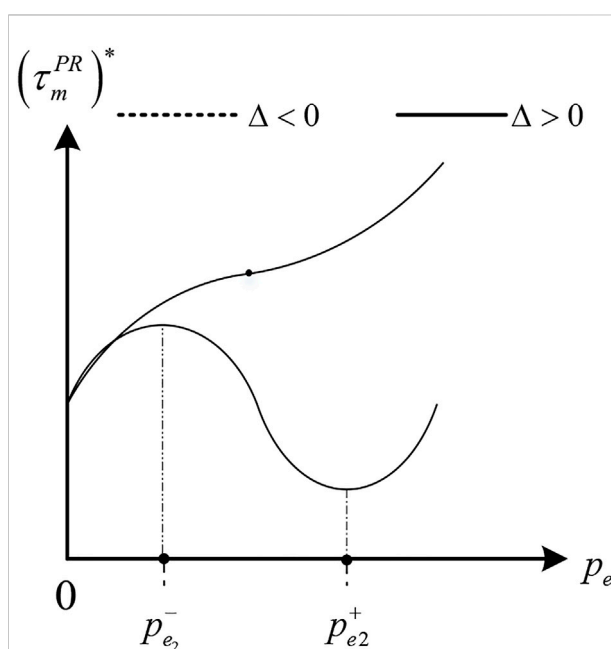
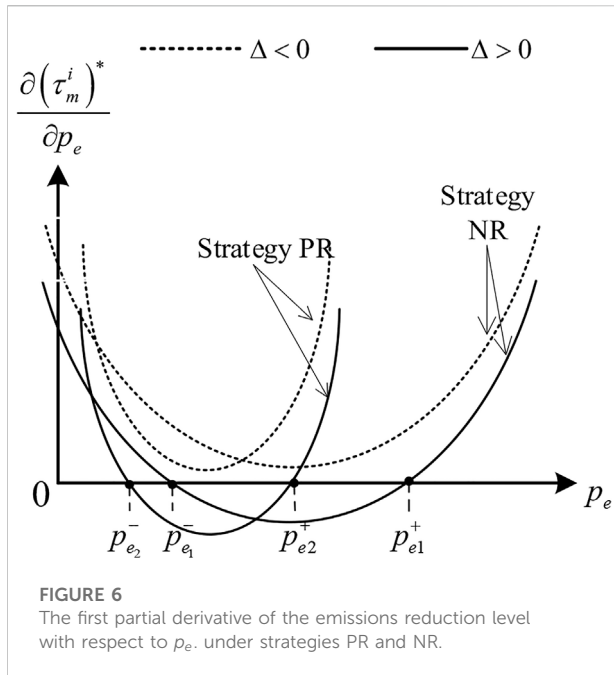


FIGURE 5
Emissions reduction level under strategy PR.

Proposition 6. The impacts of the carbon credit market price on emissions reduction levels under strategy PR are summarized in this proposition.



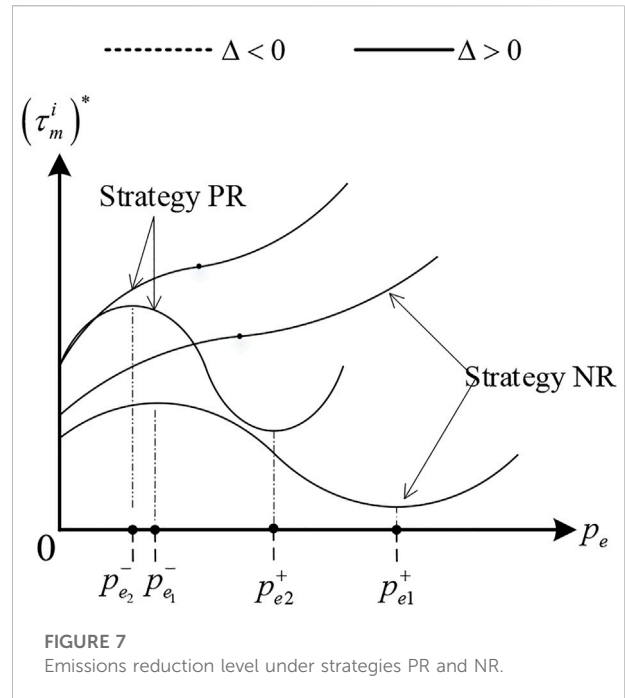
- 1) If $h_m < \frac{(a+1)^2}{2}$, then $\frac{\partial(\tau_m^{NR})^*}{\partial p_e} > 0$, which indicates $(\tau_m^{NR})^*$ increases with the increase of p_e .
- 2) If $h_m > \frac{(a+1)^2}{2}$, then in the interval $(\frac{(2h_m-a-1)-\sqrt{2h_m[2h_m-(a+1)^2]}}{a+1}, \frac{(2h_m-a-1)+\sqrt{2h_m[2h_m-(a+1)^2]}}{a+1})$, we have $\frac{\partial(\tau_m^{NR})^*}{\partial p_e} < 0$ and in other intervals it is the opposite.
- 3) If $h_m < \frac{2h_r(a+1)^2}{4h_r-1}$, then $\frac{\partial(\tau_m^{PR})^*}{\partial p_e} > 0$, which indicates $(\tau_m^{PR})^*$ increases with the increase of p_e .
- 4) If $h_m > \frac{2h_r(a+1)^2}{4h_r-1}$, then in the interval $(\frac{-[h_m(1-4h_r)+2h_r(a+1)]-\sqrt{h_m(4h_r-1)[-2h_r(1+a)^2+h_m(4h_r-1)]}}{2h_r(a+1)}, \frac{-[h_m(1-4h_r)+2h_r(a+1)]+\sqrt{h_m(4h_r-1)[-2h_r(1+a)^2+h_m(4h_r-1)]}}{2h_r(a+1)})$, we have $\frac{\partial(\tau_m^{PR})^*}{\partial p_e} < 0$ and in other intervals it is opposite.

In Figure 4 and Figure 5, we illustrate the observations in Proposition 6.

When $p_e = 0$, then $(\tau_m^{NR})^* = \frac{a}{4h_m-2}$, and $(\tau_m^{PR})^* = \frac{a_r}{4h_m-2-\frac{h_m}{h_r}}$. It is clear that $(\tau_m^{PR})^*|_{p_e=0} > (\tau_m^{NR})^*|_{p_e=0}$.

From the proof mentioned previously, the distance between $(p_{e_1}^-, 0)$ and $(p_{e_1}^+, 0)$ is: $A = \frac{2\sqrt{2h_m[2h_m-(a+1)^2]}}{a+1} = \frac{\sqrt{8h_m[2h_m-(a+1)^2]}}{a+1}$. And the distance between $(p_{e_2}^-, 0)$ and $(p_{e_2}^+, 0)$ is: $B = \frac{\sqrt{h_m(4h_r-1)[-2h_r(1+a)^2+h_m(4h_r-1)]}}{h_r(a+1)} = \frac{\sqrt{8h_m[2h_m-(a+1)^2]+\frac{h_m}{h_r}[2h_r(1+a)^2-h_m(8h_r-1)]}}{a+1}$.

When $-2h_r(1+a)^2 + h_m(4h_r-1) > 0$, then $2h_r(1+a)^2 - h_m(8h_r-1) < 0$. Therefore, $A > B > 0$, which implies that the opening degree of y_2 is lower than that of y_1 . We can know that $p_{e_2}^- < p_{e_1}^-$ and $p_{e_1}^+ > p_{e_2}^+$. The emissions reduction level changes with the carbon credit market price



under strategy NR and strategy PR are summarized in Figure 6 and Figure 7.

As shown in the aforementioned figures, the optimal emissions reduction level under the strategy PR is higher than that under the strategy NR. That is to say, if a retailer adopts a promotion strategy, the low-carbon demand and production quantity will increase. Compared with strategy NR, the manufacturer has more willingness to invest in reducing carbon emissions under strategy PR, and the optimal emissions reduction level is higher under the strategy PR. We also find that the emissions reduction level under strategy PR is more sensitive to the carbon credit market price. Owing to the retailer making efforts to promote low-carbon products, the manufacturer has incentives to invest in emissions reduction and the marginal utilities diminish more rapidly than those under strategy NR. Then, the emissions reduction level reaches a peak faster. In other words, with the retailer promoting low-carbon products, the negatively correlated area will decrease, which makes the optimal emissions reduction level higher at a relatively low-carbon credits market price than the case the retailer does not promote.

Modeling calibration and discussions

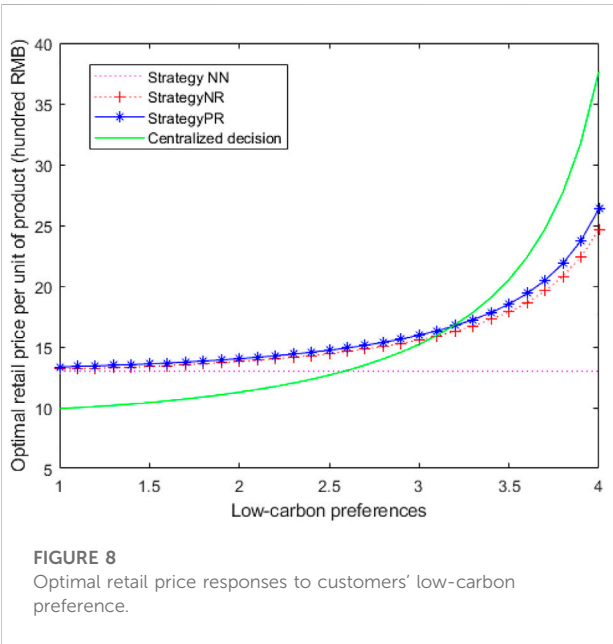
Data description

Based on the obtained theoretical results, this section uses MATLAB software to carry out numerical examples to

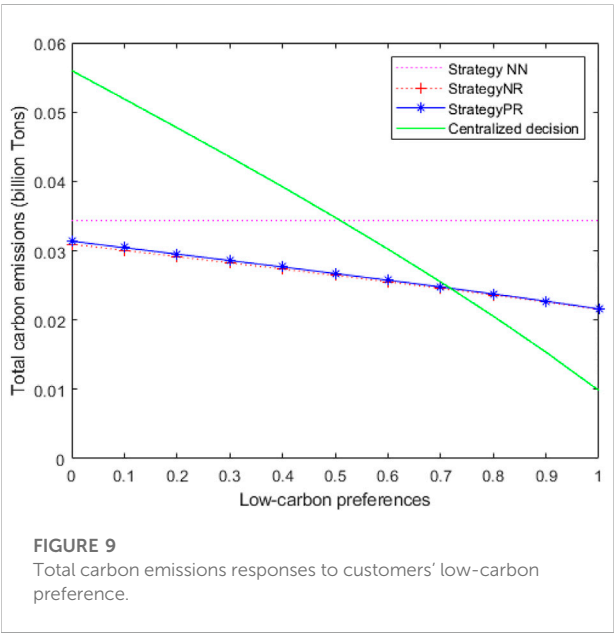
TABLE 2 Input parameters of the simulation.

Variables	Value	Unit	Variables	Value	Unit
a	10	Million	e_m	0.01	Ton
b	0.6	—	h_m	20	—
γ	[0,4]	—	h_r	10	—
β	0.6	—	p_e	60	RMB/Ton
c_m	0.9	Thousand RMB	C_g	1,000	Thousand Ton
c_r	0.6	Thousand RMB	—	—	—

^aData source: Greco Consulting (Beijing) Co., Ltd., and the China Household Electrical Appliances Association (CHEAA).



focus on comparing the impact of CAT and consumers' low-carbon preference on the optimal strategy, profit, total carbon emissions, and social welfare of enterprises under different strategies. We apply the Stackelberg model to the Chinese refrigerator industry. In 2021, the Chinese company JD sold 13 million refrigerators online. Then, the potential market demand was set as 10 million. Since China launched CAT in Shanghai, the carbon trading price in Shanghai's Carbon Trading Center has been 59.5 RMB/Ton (Greco Consulting (Beijing) Co., Ltd.). Based on the baseline method, the manufacturer can be allocated free carbon credits that are set as 1 million tons. It takes 14 kWh to produce one refrigerator (Zhang et al., 2016). Thus, $e_m = 14 \text{ kWh} \times 0.785 \text{ kWh/kg}$ (Calculation of carbon emissions 2014). One-third of a refrigerator's manufacturing cost is the price of a compressor, which is 300 RMB yuan (Zhang et al., 2016). The production cost can be set as 900 RMB yuan. The values of these input parameters are shown in Table 2.



The impact of customers' low-carbon preference on the retail price per unit of a product

To investigate the influence of customers' low-carbon preference on the optimal retail price, we set the interval of customers' low-carbon preference as [1, 4] with an interval of 0.1. Figure 8 presents that under decentralized decision-making, if the manufacturer does not invest in reducing carbon emissions, there will be no low-carbon products in the market. Then, the consumers' low-carbon preference has no impact on the retail price per unit of a product of strategy combination NN and strategy combination PN. Since the implementation of the manufacturer's carbon emissions reduction strategy and the retailer's promotion strategy requires a certain investment, they will pass the investment cost to the consumer. Then, the retail price per unit of the product under the centralized decision-making mode and PR strategy is generally higher than other strategy combinations when the retailer does take measures to promote low-carbon products.

It is interesting that when customers' low-carbon preference varies in the range of $[1, 4]$, the retail price per unit of the product under the NN strategy is higher than that of other strategy combinations. It is very likely that there are only ordinary products in the market, and the manufacturer and the retailer make more profits by raising the wholesale price and retail prices. After that, the retail price increases with the increase in consumers' low-carbon preferences. At this time, the manufacturer invests more in reducing carbon emissions, and retail starts promoting low-carbon products to make profits through "small profits but quick turnover". However, since the low-carbon technologies gradually meet the ceilings, the increase in investment costs for carbon emissions reduction and promotion, and retail costs will cause the profit margins of the manufacturer and retailer to gradually be compressed. Therefore, the retail price has to increase.

In the centralized decision-making mode, when customers' low-carbon preference varies in the range of $[1, 3.2]$, the retail price per unit of a product is always lower than that in the decentralized decision-making mode, but the profit is the highest. It indicates that, when the retailer and the manufacturer cooperate, the products will be cheap and environmentally friendly, so the demand will increase, and the total profit of the supply chain will be sustainable. We also find that, under a centralized decision-making mode, when the low-carbon preference coefficient is over 3.2, the optimal retail price per unit of the product will exceed any other strategy combinations. It means that, when consumers' low-carbon preference coefficient is high enough, the retail price per unit of low-carbon products will be higher than that of ordinary products.

The impact of customers' low-carbon preference on the total carbon emissions

To investigate the influence of customers' low-carbon preference on the total carbon emissions, we set the interval of the customers' low-carbon preference as $[0, 1]$ with an interval of 0.1.

Figure 9 shows that under decentralized decision-making, when the manufacturer does not adopt carbon emissions reduction technologies, the total carbon emissions are higher than in the other two cases. When the consumers' low-carbon preference varies between $[0, 0.7]$, the total carbon emissions under the centralized decision-making mode are higher than those under the decentralized decision-making mode. This is because, under a centralized decision-making mode, although consumers are willing to pay more for low-carbon products, the manufacturer and the retailer need to share the benefits of the premium consumers' pay. In other words, the shared benefits are not enough to balance the investment costs for carbon emissions reduction and promotion, so the effect of carbon emissions reduction is not much higher than that under decentralized

decision-making. In the short term, under a certain emissions reduction level, the promotion will increase the production quantity and total carbon emissions. On the contrary, under a decentralized decision-making mode, the manufacturer can share most of the premium consumers' pay. In addition, the effect of carbon emissions reduction will not be too bad. Although the sales volume is not as good as that of the centralized decision-making mode, the total carbon emissions will be slightly lower. Under the decentralized decision-making mode, as consumers' low-carbon preferences continue to increase, manufacturer's carbon emissions reduction actions are slow. When the customers' low-carbon preferences coefficient is higher than 0.7, the total carbon emissions are higher than those in the centralized decision-making mode.

The impacts of the carbon credit market price and customers' low-carbon preference on total carbon emissions

To investigate the combined impacts of the carbon credit market price and customers' low-carbon preferences on total carbon emissions, we set the interval of customers' low-carbon preferences as $[0, 2]$ with an interval of 0.1, and carbon credit market price as $[50, 70]$ with an interval of 1. Figure 10 shows that the customers' low-carbon preferences have a greater impact on the total carbon emissions. Regardless of the carbon price, consumers who are willing to pay more for low-carbon products can always reward the manufacturer and retailer.

Within a limited range, the total carbon emissions of the supply chain decrease as consumers' low-carbon preference and carbon credit market price both increase, except in the NN mode. It means that as long as the manufacturer adopts a reduction strategy, total carbon emissions will finally be reduced. This is because, if the manufacturer does not reduce emissions, once the emissions exceed the cap, he will have to buy the carbon credits at a high price. If the manufacturer adopts a reduction strategy, he can earn additional revenue by selling the surplus carbon credits at a high market price. On the other hand, the manufacturer and retailer could gain the benefits from premium consumers who will pay for low-carbon products. The higher the carbon price and consumers' low-carbon preference, the more incentive for the manufacturer to reduce emissions and the retailer to promote low-carbon products. Then, the total carbon emissions will become lower and lower.

The impact of customers' low-carbon preference on social welfare

To investigate the influence of customers' low-carbon preference on the total profit of the manufacturer and the retailer, we set the interval of the customers' low-carbon

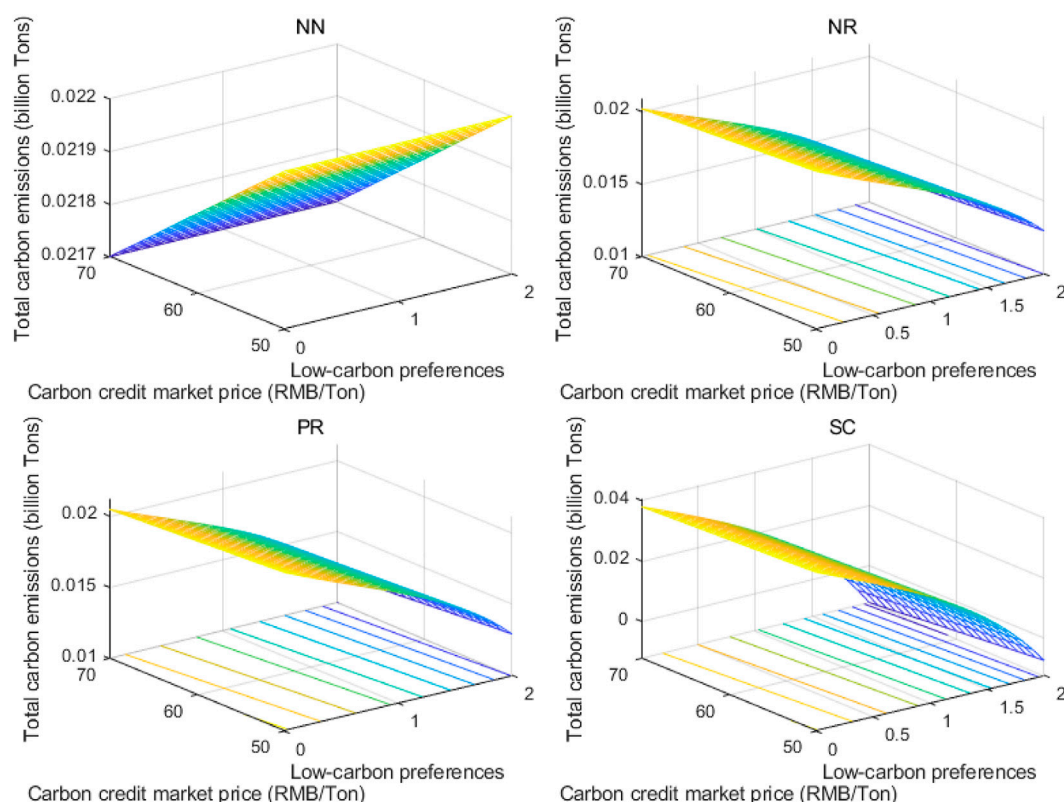


FIGURE 10

Total carbon emissions responses to customers' low-carbon preference and carbon trading price.

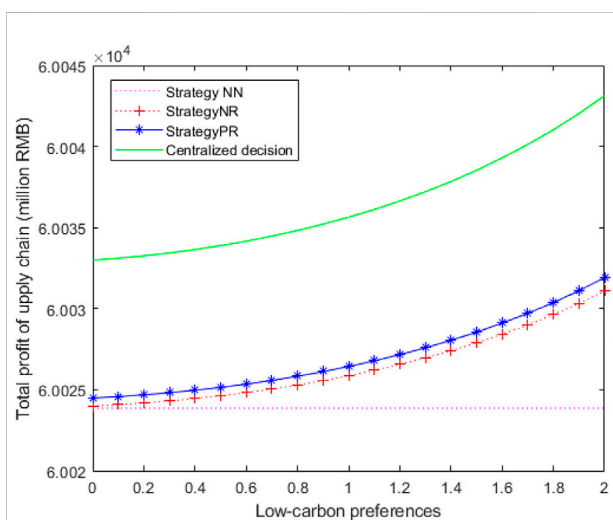


FIGURE 11

Profits of supply chain responses to customers' low-carbon preference.

preference as $[0, 2]$ with an interval of 0.1. Figure 11 shows that within a limited range, the overall profit of the supply chain increases as consumers' low-carbon preference increases, and

the profit of the supply chain under centralized decision-making is always higher than that under decentralized decision-making.

Under decentralized decision-making, if the manufacturer does not invest in reducing carbon emissions, there will be no low-carbon products in the market. Then, consumers' low-carbon preference has no impact on the supply chain profits of the strategy combination NN and strategy combination PN. As consumers become more environmentally aware and become willing to pay more for low-carbon products, market demand is most affected by customers' low-carbon preferences. If the retail price per unit of a product increases within a reasonable range, consumers will also be willing to buy. It is easy to find that when the retail price per unit of a product no longer dominates the consumers' buying behavior, the market will be similar to the auction market. That is, as long as consumers like low-carbon products, the products will not be unsalable, which is very friendly to the manufacturer and retailer. The profit of the supply chain will increase unabated. However, in real life, on one hand, low-carbon products do not occupy the entire market. On the other hand, consumers tend to consume rationally. So, to buy products with the highest cost performance, consumers will have to

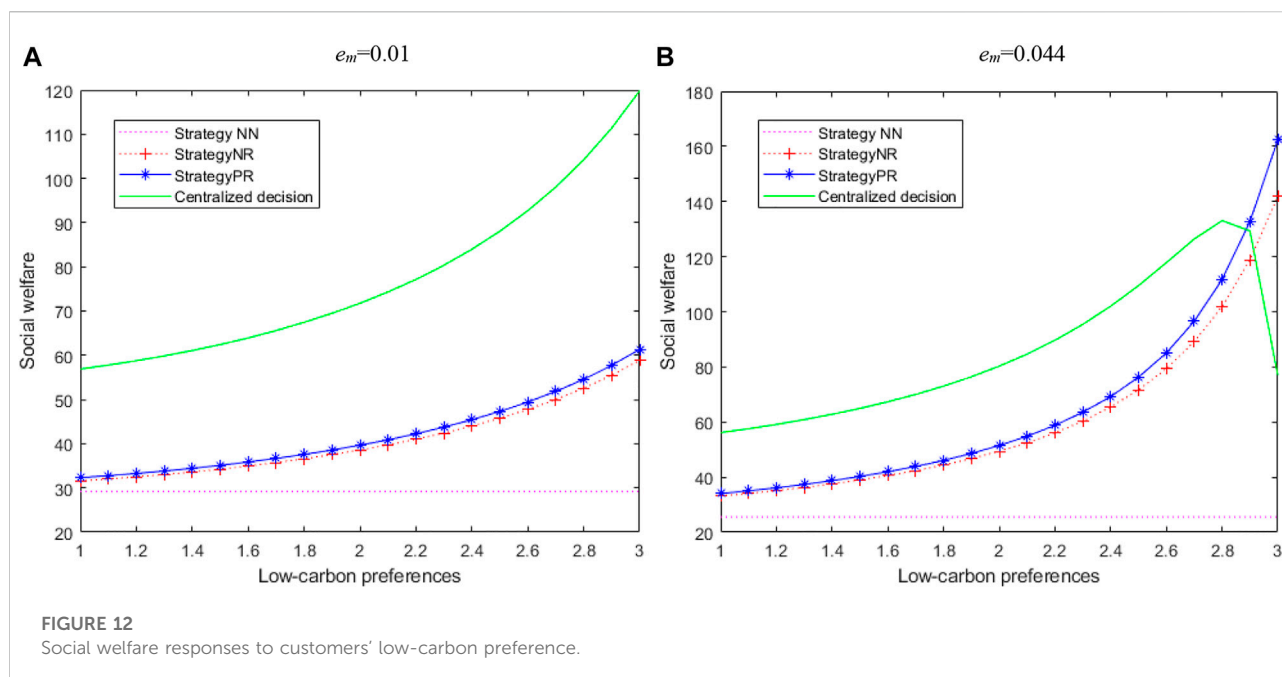


FIGURE 12
Social welfare responses to customers' low-carbon preference.

trade-off between the retail price and emissions reduction level.

Without considering externalities, social welfare is the sum of producer surplus and consumer surplus (Tang and Du, 2019). The social welfare in this study can be expressed by Equation 17:

$$S = \int_0^{q^*} \left(\frac{a - x + \gamma\tau_m + \beta\tau_r}{b} - c_m - c_r \right) dx - \frac{1}{2}h_m\tau_m^2 - \frac{1}{2}h_r\tau_r^2 \quad (14)$$

We can rewrite social welfare as

$$S = \left(\frac{a + \gamma\tau_m + \beta\tau_r}{b} - c_m - c_r \right) q^* - \frac{q^{*2}}{2b} - \frac{1}{2}h_m\tau_m^2 - \frac{1}{2}h_r\tau_r^2 \quad (15)$$

Then, the social welfare of each strategy is as follows:

$$S_{NN} = S_{PN} = \left(\frac{a}{b} - c_m - c_r \right) q_{NN}^* - \frac{(q_{NN}^*)^2}{2b} \quad (16)$$

$$S_{NR} = \left(\frac{a + \gamma\tau_m}{b} - c_m - c_r \right) q_{NR}^* - \frac{(q_{NR}^*)^2}{2b} - \frac{1}{2}h_m\tau_m^2 \quad (17)$$

$$S_{PR} = \left(\frac{a + \gamma\tau_m + \beta\tau_r}{b} - c_m - c_r \right) q_{PR}^* - \frac{(q_{PR}^*)^2}{2b} - \frac{1}{2}h_m\tau_m^2 - \frac{1}{2}h_r\tau_r^2, \text{ and} \quad (18)$$

$$S_{SC} = \left(\frac{a + \gamma\tau_m + \beta\tau_r}{b} - c_m - c_r \right) q_{SC}^* - \frac{(q_{SC}^*)^2}{2b} - \frac{1}{2}h_m\tau_m^2 - \frac{1}{2}h_r\tau_r^2 \quad (19)$$

The influence of customers' low-carbon preference on social welfare is shown in Figure 12.

Figure 12A shows that when the initial carbon emissions of a product are 0.01, that is the level of emissions reduction is high, the social welfare under centralized decision-making is always higher than that under decentralized decision-making. As long as the manufacturer and retailer adopt sustainable strategies, it is good for society and the environment. However, Figure 12B shows that when the level of emissions reduction is low ($e_m = 0.044$) and customers' low-carbon preference continues to increase beyond 2.8, the social welfare under centralized decision-making declines rapidly. This is because, although consumers are willing to pay more for low-carbon products, consumer surplus decreases as purchase cost increases. The figure shows that as consumers' low carbon preference increases, the profits of the supply chain will increase accordingly, but this increased profit comes at the expense of consumer surplus. Therefore, if the profits of the manufacturer and retailer increase based on the remaining consumer surplus unchanged or slightly increased, the social welfare will be Pareto-improved. That is, while reducing production costs or raising retail prices, the manufacturer and retailer can increase consumer utility by the same amount by investing in carbon emissions reduction or promoting low-carbon products.

These observations offer the following management insights for policy-makers and entities in low-carbon products who promote and produce.

- 1) When the consumers' low-carbon preference coefficient is low, the manufacturer can single-handedly minimize the total carbon emissions of the supply chain by adopting low-carbon technology. At the same time, the retailer can take a free ride.

- 2) When the carbon price and consumers' low-carbon preference are high enough, the optimal retail price will always be higher than that of ordinary products. Each stakeholder can make decisions to maximize self-profits. However, it inevitably brings about a double-marginal effect and affects the total profits of the supply chain in any collaboration mode under a decentralized scenario.
- 3) To obtain the highest total profits and lowest carbon emissions, the manufacturer and retailer can centrally make the strategic decisions of emissions reduction and promotion decisions. But the social welfare declines rapidly because it is affected by the initial carbon emissions per unit of a product and the carbon trading price of the CAT mechanism.
- 4) To keep social welfare from being reduced, retailers can appropriately lower the retail price, or stakeholders can save the cost of investing in reducing carbon emissions and promoting low-carbon products. Social welfare will increase when the level of emissions reduction in society is high enough, which requires all manufacturers to make efforts to adopt low-carbon technology. At the same time, retailers and customers need to be environmentally friendly.

In brief, under the CAT mechanism, manufacturers and retailers need to adjust their strategic decisions of emissions reduction and promotion at any time according to the initial carbon emissions of a product and different consumers to balance the trade-off between social and environmental benefits of the retailer-led supply chain.

Conclusion

Governments, enterprises, and customers pay more attention to protecting the environment, such as manufacturers investing in low-carbon technologies, retailers making efforts to promote low-carbon products, and consumers having low-carbon preferences. Specifically, among other strategies, CAT has reduced carbon emissions effectively. Considering CAT and consumer environmental preferences, we developed a Stackelberg game model that characterizes gaming and cooperative behaviors of the manufacturer and retailer. The equilibrium solutions under each strategy combination in a decentralized decision-making mode have been solved. The key findings are summarized in the following terms. 1) It is the most economical and environmentally friendly when the manufacturer makes efforts to reduce emissions and the retailer invests in promoting low-carbon products. 2) Sensitivity experiments showed that the CAT mechanism, emissions reduction level, the promotional effort level, and the customers' environmental preferences could influence the

optimal solutions of the manufacturer and retailer in the decentralized decision-making mode and cooperative mode. 3) The manufacturer is willing to invest in reducing emissions when the carbon trading prices are high. However, the emissions reduction level does not always increase with carbon trading prices unless the allocation of carbon credits is sufficient. 4) When the customers' low-carbon preference coefficient is large enough, the total carbon emissions are highest when the manufacturer and retailer make decisions together, and the social welfare of the centralized decision-making mode is lower than that of a decentralized decision-making mode when the retailer takes a promotion strategy and the manufacturer takes an emissions reduction strategy. These findings can be useful for both the government and stakeholders in the supply chain.

There are several interesting extensions to this work. We assume that: 1) the levels of emissions reduction and promotion efforts are the same for all low-carbon products, 2) stakeholders are perfectly rational, and 3) markets and CAT have not changed over time. Then, more actual models can be developed to understand the stakeholders' behavior and predict the market trend. Second, in a real market, the supply chain, consisting of multiple stakeholders, the coordination, and profit-sharing mechanism of the supply chain network based on a multi-agent game, needs further research. Finally, we only considered one carbon emissions policy. Other nuanced models could be constructed to identify how stakeholders make better long-term decisions under complex policies to reduce carbon emissions.

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

Conceptualization, WT and HL; methodology, software, and formal analysis, WT; data curation, JD; writing—original draft preparation, WT; writing—review and editing, HL and JD; supervision, HL; funding acquisition, HL. All authors have read and approved the final manuscript.

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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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Appendix A: For ease of reference, Equation (x) in the article is referred to as (E.x) in this appendix

Proof of Proposition 5

From our previous research (Tong and Mu, 2019), we can get the optimal carbon emissions reduction under strategy NR is $(\tau_m^{NR})^* = \frac{(1+p_e)(a-p_e)}{4h_m-2(1+p_e)}$. Then, the first partial derivative of $(\tau_m^{NR})^*$ with respect to p_e is shown as follows:

$$\frac{\partial(\tau_m^{NR})^*}{\partial p_e} = \frac{(1+a)p_e^2 + [2(1+a)-4h_m]p_e + 2h_m(a-1)+a+1}{2[(1+p_e)^2 - 2h_m]^2}.$$

Let $y_1 = (1+a)p_e^2 + [2(1+a)-4h_m]p_e + 2h_m(a-1)+a+1$, where $(1+a) > 0$.

When $h_m < \frac{(a+1)^2}{2}$, then $\Delta = 8h_m[2h_m - (a+1)^2] < 0$. The quadratic curve $y_1(p_e)$ has no roots, which implies that there is always $y_1 > 0$. We can easily find that $\frac{\partial(\tau_m^{NR})^*}{\partial p_e} > 0$.

When $h_m > \frac{(a+1)^2}{2}$, then y_1 has two roots $(p_{e1}^-, 0)$ and $(p_{e1}^+, 0)$, that is $(\frac{(2h_m-a-1)+\sqrt{2h_m[2h_m-(a+1)^2]}}{a+1}, 0)$ and $(\frac{(2h_m-a-1)-\sqrt{2h_m[2h_m-(a+1)^2]}}{a+1}, 0)$. This implies that in the interval $(\frac{(2h_m-a-1)-\sqrt{2h_m[2h_m-(a+1)^2]}}{a+1}, \frac{(2h_m-a-1)+\sqrt{2h_m[2h_m-(a+1)^2]}}{a+1})$, we have $\frac{\partial(\tau_m^{NR})^*}{\partial p_e} < 0$. In other intervals it is opposite.

Q.E.D.

Proof of Proposition 6

From our previous research (Tong and Mu, 2019), we can get the optimal carbon emissions reduction under strategy PR, which is $(\tau_m^{PR})^* = \frac{h_r(1+p_e)(a-p_e)}{2h_r[2h_m-(1+p_e)^2]-h_m}$. Then, the first partial derivative of emissions reduction level with respect to p_e under strategy PR is shown as follows:

$$\frac{\partial(\tau_m^{PR})^*}{\partial p_e} = \frac{2(1+a)h_r p_e^2 + [-2h_m(4h_r-1) + 4(a+1)h_r]p_e + h_m(a-1)(4h_r-1) + 2h_r(a+1)}{\frac{[h_m(4h_r-1)-2h_r(1+p_e)^2]^2}{h_r}}$$

Let $y_2 = 2(1+a)h_r p_e^2 + [-2h_m(4h_r-1) + 4(a+1)h_r]p_e + h_m(a-1)(4h_r-1) + 2h_r(a+1)$. Note that we do not consider $4h_r-1 < 0$ because the promotion cost coefficient is always greater than 1.

When $h_m < \frac{2h_r(a+1)^2}{4h_r-1}$, then $\Delta = h_m(4h_r-1)[-2h_r(1+a)^2 + h_m(4h_r-1)] < 0$. There always exists $\frac{\partial(\tau_m^{PR})^*}{\partial p_e} > 0$.

When $h_m > \frac{2h_r(a+1)^2}{4h_r-1}$, then $\Delta = h_m(4h_r-1)[-2h_r(1+a)^2 + h_m(4h_r-1)] > 0$. y_2 also has two roots $(p_{e2}^-, 0)$ and $(p_{e2}^+, 0)$. In the interval $(-[h_m(1-4h_r) + 2h_r(a+1)], \frac{-\sqrt{h_m(4h_r-1)[-2h_r(1+a)^2 + h_m(4h_r-1)]}}{2h_r(a+1)})$, we can get $\frac{\partial(\tau_m^{PR})^*}{\partial p_e} < 0$ and in other intervals it is the opposite.



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A symmetric and asymmetric nexus between environmental sustainability and tourism development in BRIC nations: What is the role of good governance and globalization?

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The motivation of the study was to gauge the impact of environmental quality (EQ), good governance (GG), and globalization (GLO) on tourism development in BRIC nations for the period 1990–2021. The study implements linear and nonlinear frameworks for evaluating the elasticity of explanatory variables on tourism and the directional association by using the non-granger causality test. Combined cointegration test statistics show a long-run association between EQ, GG, and GLO and tourism development in BRIC nations. Furthermore, the long-run association in the empirical estimation is established in both linear and nonlinear framework assessments. Referring to linear assessment, the study documents the positive, statistically significant linkage between good governance, globalization, and tourism development, implying that political stability, governmental effectiveness, and accountability foster tourism development. Furthermore, global economic and financial integration opens a window for tourism development by inducing the economy's international tourism. On the other hand, environmental degradation reveals adverse statistically significant influences on tourism development, suggesting that the environmental stability in the form of healthy and amicable ambiance positively triggers tourism development, especially in the long run. According to the test statistics of the standard Wald test, it is obvious that there is an asymmetric association between explanatory variables such as EQ, GG, and GLO and tourism development in the long-run and short-run assessment. The directional causality test documented bidirectional causality in explaining the causality between environmental quality and tourism development in Brazil, India, and China, good governance and tourism development in India, and globalization and tourism development in China. On a policy note, the study advocated that BRIC has to ensure environmental protection and governmental effectiveness to promote sustainable development in the tourism sector.

KEYWORDS

environmental quality, globalization, good governance, tourism, symmetric and asymmetric ARDL, TY-causality

1 Background of the study

Around the world, tourism has seen more rapid expansion worldwide than many other industries (Zappino, 2005). According to the so-called tourist-led growth theory, tourism is one of the primary drivers of global economic development because of its involvement in the creation of employment, the increase in revenues from exports, and the promotion of infrastructure improvements (Dwyer et al., 2004; Belloumi and Alshehry, 2016; Chiu and Yeh, 2017). Over the last decade, international tourism has solidified its position as one of the primary factors of sustainable socioeconomic growth. Compared to the previous year, 2020, 2021 saw a growth in tourism of 4 percent all over the globe (415 million against 400 million). According to UNWTO (2022), the number of foreign tourist arrivals (overnight tourists) in 2019 remained 72 percent lower than the year before the epidemic. This is a direct consequence of the year 2020, which was the worst year for tourism and saw a decrease of 73 percent in the number of foreign travelers. In addition, the predicted economic contribution of tourism in the year 2021 is \$1.9 trillion. This figure represents an increase from \$1.6 trillion in 2020 but a considerable fall from the value of \$3.5 trillion before the pandemic. Foreign tourist export sales might reach over US\$700 billion in 2021, a little increase over 2020 owing to a greater spending per trip, but less than half of the US\$1.7 trillion achieved in 2019, in terms of the growth of tourism in the BRIC countries.

The impact of tourism development has extensively invested with the trade-off of diverse macro fundamentals such as economic growth (Lee and Chien, 2008; Chou, 2013; Teng et al., 2021), human capital development (Li and Qamruzzaman, 2022a), financial development, inflows of FDI (Yang et al., 2021), energy consumption (Meo et al., 2021), and environmental sustainability (Nguyen and Dinh Su, 2021; Liu et al., 2022; Villanthenkodath et al., 2022). Acknowledging the deniable and significant contribution of tourism development, many researchers have investigated the role of macro fundamentals, particularly the key determinants for tourism development (Chen, 2017; Sokhanvar, 2019; Akadiri et al., 2020; Jena et al., 2021; Meo et al., 2021). The study of Parida et al. (2017), for instance, has investigated the key determinants of tourism development in India with a panel of 25 states for the period 1995–2011. The study documented that economic growth, cultural practices, and natural resources are critical for tourism development. In the case of Laos tourism development, Phakdisoth and Kim (2007) revealed that infrastructural development, communication, economic stability, and trade openness are significant.

The present study has considered globalization, good governance, and environmental quality in tourism development. Because of globalization, people from all over the globe can more easily share their thoughts and ideas on various topics, including politics, the environment, technology, culture, and economics. (Zhao and Li, 2006), moreover, both

globalization and tourism are tied to one another. This relationship has, thus, enabled the worldwide transmission of large quantities of knowledge through fostering mutual understanding. Political miscommunication across regions significantly hinders global tourism growth (Wood, 2008; Jena et al., 2021). Diverse countries' citizens are abandoning their ethnic, tribal, religious, and political cocoons to embrace humanity. Many people see the advantages of cooperating rather than antagonizing one another on false difficulties. Tourism and globalization have profited from this trend (Javid and Katircioglu, 2017; Chiu et al., 2021). So far, empirical data on the relationship between environmental quality measured by carbon dioxide emissions and tourism development have been ambiguous. According to Tian et al. (2021), increased tourist development tends to reduce carbon dioxide emissions, proving that tourism is not harmful to the environment and assists in pollution reduction in the G20 countries analyzed. Due to the G20 nations' move away from fossil fuels, the tourism industry, which depends on energy more than any other sector, has started incorporating renewable energy sources. However, Yue et al. (2021) found that tourism does not contribute much to greenhouse gas emissions. Countries are advised to forsake their nonrenewable energy in favor of renewable energy sources, which will help decrease the pace of environmental degradation.

COP26 is occurring at a vital moment, and the tourist sector is seeing an exceptional rebound, making it simpler to adopt operational changes. It is a perfect time for the public and commercial sectors to reset their operations to make them more ecologically sustainable and to improve their communication and relationships since they do not have to cope with high levels of tourist demand. Tourism is more likely to meet its sustainability objectives if these industries collaborate. According to a recent GlobalData poll*, 45 percent of respondents said the environment was the most significant ESG (environmental, social, and governance) aspect. The United Nations is responding to this rising public concern by requiring parties to agree to new environmental objectives at COP26, which include tourism as an established aspect of the plan. There is a chance that COP26 might be a turning moment in the role of sustainability in tourism. During the following decade, more concrete outcomes might be observed as a consequence of more transparent activities taken by numerous private sector businesses.

The motivation of the study was to investigate the impact of environmental sustainability, good governance, and globalization on tourism development in BRIC nations with the application of symmetric and asymmetric frameworks.

The study's contribution is as follows: first, existing literature has produced plenty of evidence focusing on the impact of tourism and globalization on various macro fundamentals such as economic growth, foreign direct investment, human capital development, and environment. However, the nexus

between globalization-led tourism developments has yet to investigate extensively; therefore, the present study has initiated mitigating the existing research gap with fresh knowledge. Second, the present study used linear and nonlinear frameworks to evaluate and document independent variables' elasticities in BRIC tourism development. The implementation of asymmetric assessment has offered alternative policy formulation ways to understand the positive and negative innovation effects on target variables.

The study's objective was to investigate the effects of globalization, good governance, and environmental quality in tourism development in BRIC nations for the period 1990–2021 by using linear and nonlinear frameworks. Combined cointegration test statistics show a long-run association between EQ, GG, and GLO and tourism development in BRIC nations. Furthermore, the long-run association in the empirical estimation is established in both linear and nonlinear framework assessments. Referring to linear assessment, the study documented the positive and statistically significant linkage between good governance and globalization, implying that political stability, governmental effectiveness, and accountability have been revealed as boosting factors for tourism development. Moreover, global economic and financial integration opens a window for tourism development by inducing the economy's international tourism. On the other hand, environmental degradation, which is the carbon emission in the economy, adversely affects tourism development, indicating that the healthy and amicable ambiance positively triggers tourism development in the long run. According to the test statistics of the standard Wald test, it is obvious that there is an asymmetric association between explanatory variables such as EQ, GG, and GLO and tourism development in the long-run and short-run assessment. The directional causality test documented bidirectional causality in explaining the causality between environmental quality and tourism development [EQ $\longleftrightarrow$ TOR] in Brazil, India and China, good governance and tourism development [GG $\longleftrightarrow$ TOR] in India, and globalization and tourism development [GLO $\longleftrightarrow$ TOR] in China.

The remaining structure of the study is as follows. The literature survey of the study is given in [Section 2](#). The variables' definition and methodology of the study are explained in [Section 3](#). [Section 4](#) addresses empirical model estimation and its interpretations. Discussion of the results is given in [Section 5](#). Finally, the conclusion and policy implication are available in [Section 6](#).

2 Literature survey

Global integration in the form of economic and financial perspectives has affected the overall economic activities, including the internationalization of domestic trade, the

involvement of foreign participants in economic development, the movement of cross-border capital, and political-economic development. As a result of globalization's ability to draw in players from other countries, the financial and economic spheres become more accessible to new ideas and innovations. This is especially true in the tourist industry, which has received much attention for its potential for future growth. Tourism as an increasingly significant activity reflects all of these shifts, particularly mass tourism, which can be seen in many aspects of global change. The development of tourism is illustrative of the tremendous implications of globalization, in particular, when one considers the progress that has been made in information technology, communication, and transportation, amongst other things. As an example of fast expansion and its rising importance on the global market, tourism has a significant effect on other directly or indirectly associated businesses ([Hołowiecka et al., 2011](#); [Li and Qamruzzaman, 2022b](#)).

Regarding the tourism-globalization nexus, the present study has revealed two-directional study findings; first, many researchers have investigated the role of tourism effects on globalization ([Sugiyarto et al., 2003](#)). Tourism has played an important part in the progress of globalization by allowing travel mobility, such as airports, hotels, and resorts, while governments reduced formal processes to assist the processing of a growing number of visitors ([Hannam et al., 2006](#)). Moreover, the proponents of globalization assert that it fosters global economic development, generates employment, makes businesses more competitive, extends consumer options, and reduces production costs. The study by [Meethan \(2004\)](#) asserted that globalization intensifies macroeconomic activities by transferring technical knowledge, expanding the market, promoting innovation, and fostering international understanding.

Second, a group of researchers has investigated the role of globalization on tourism development ([Zhao and Li, 2006](#); [Wood, 2008](#); [Knežević, 2015](#); [Javid and Katircioglu, 2017](#); [Chiu et al., 2021](#); [Jena et al., 2021](#)). The study of [Chiu et al. \(2021\)](#), for instance, has investigated the impact of globalization on tourism development with the application of panel dynamic threshold analysis. The study documented that economic global integration boost tourism development; in particular, the level of global integration has revealed the different levels of elasticity on tourism development. As a result of globalization, the tourism and economic sectors have also had a significant impact on marketing efforts, the dissemination of technical know-how, expanded access to transportation and infrastructure, boosted investment motivations, broadening and diversifying the range of tourism products, increasing employment in the industry, and many other aspects of the industry ([Mustafa, 2010](#); [Dwyer, 2015](#)). There are many variables to consider regarding the connection between globalization and tourism.

Concerning issues about environmental quality and tourism, researchers have uncovered two distinct lines of inquiry: the

impacts of tourism on environmental quality, as indexed by carbon emissions; and the influence of environmental quality on the expansion of tourists. Referring to first the empirical nexus that is tourism-led environmental quality, a growing number of researchers have established positive and statistically significant associations (Paramati et al., 2017a; Mishra et al., 2020; Sharif et al., 2020). Numerous academics have examined the impact of tourism on carbon emissions on the environment. Tourism is a huge social and economic enterprise (Gössling et al., 2002; Paramati et al., 2017b). According to Katircioğlu (2014), the arrival of foreign tourists in Cyprus significantly impacts energy consumption and carbon emissions. According to Balli et al. (2019), this effect positively impacts CO₂ emissions in Mediterranean countries due to tourism. From 1960 to 2014, Uzar and Eyuboglu (2019) showed that tourism increase had a positive long-term and short-term effect on carbon emissions in Turkey. Furthermore, from 1975 to 2012, Sajjad et al. (2014) investigated the relationship between air pollution and tourist growth in South Asia, North Africa, the Middle East, Sub-Saharan Africa, the Pacific regions, and East Asia. According to these studies, tourism expansion could lead to environmental degradation and biodiversity loss (e.g., Mikayilov et al. (2019) for Azerbaijan, Malik et al. (2016) for Austria, Katircioglu et al. (2018) for the major tourist destination countries, Zhang et al. (2019) for China, and Villanthenkodath et al. (2022) for India.

Considering the environmental quality-led tourism development, several researchers have investigated the effects of environmental quality on tourism development and documented a positive association between them. These findings suggest that the quality of the environment prompts tourism development by inducing foreign tourist visitors to the host economy. (Suharyono and Digidowiseiso, 2021). Tourism may theoretically be affected by the sustainability of a country's natural resources, such as its water and forest supplies (Gössling and Hall, 2006; Xia et al., 2022). As a result, governments need to increase their consumption of environmental goods to foster economic growth. When many tourist metrics are used in calculations, the link between environmental quality and tourism becomes more intriguing and complicated. In this context, several studies focus on individual visitors, including travel behavior, travel intention, destination choice (Becken et al., 2017), well-being and quality of life (Agarwal et al., 2021), visitors' satisfaction (Wu et al., 2018; Qamruzzaman, 2022a), and the image of the destination (Zhang et al., 2015; Becken et al., 2017; Deng et al., 2017). Others, on the other hand, concentrate on the demand for global tourists, including tourist arrivals, the number of visitors, international tourism revenues, urban activities, and the demand for outgoing tourists (Yan et al., 2020; Li and Qamruzzaman, 2022b). This study will concentrate on global tourist demand, particularly, in terms of the number of arriving visitors and their duration of stay.

Institutional, political-economic stability, and governmental effectiveness have documented key determinants for tourism

development which can be observed through the direct, indirect, and dynamic channels. Through the active engagement of financial intermediation, capital creation, and foreign contribution to the construction of infrastructure, amongst other things, good governance guarantees that economic growth is carried out in an equal manner. (Law and Azman-Saini, 2012; Albassam, 2013; Fayissa and Nsiah, 2013; Khalid and Shafiullah, 2021; Akadiri et al., 2022; Qamruzzaman, 2022a). The dynamic effects of good governance on tourism development can be explained by the lower level of investment causing a downward trend in aggregated economic progress and, eventually, a lower level of income generation. According to Olatunji and Falabi (2014), ineffective governance increases the higher degree of corruption, tarnishing the economic image in the international arena. The final results appear with a lower level of long-run foreign investment. In another study, Das and Dirienzo (2010) established that corruption hinders a nation's ability to compete in the tourism industry in two key ways: it tarnishes the national image and has a detrimental influence on the kind of business environment that is crucial to the success of the tourism industry.

As a determinant of environmental sustainability, Kirikkaleli and Adebayo (2021) documented the role of renewable energy consumption and financial development in environmental protection. In another study, Shan et al. (2021) suggested strengthening fiscal decentralization, lowering non-renewable energy prices, and improving institutional quality to check the deteriorating environmental quality in the study sample and other regions worldwide.

With the consideration of existing literature, we have noticed the following limitations. First, referring to the existing literature, it is manifested that researchers have investigated the nexus of tourism-led environmental sustainability, but the impact of environmental quality and tourism development has been ignored. The present study has focused on addressing the role of a quality environment in the tourism development process in BRIC nations. Second, existing literature postulates that empirical studies have been initiated focusing on environmental sustainability, good governance, and globalization under the symmetric environment. At the same time, the present study focused on both symmetric and asymmetric frameworks in exploring the variable's elasticities on tourism development.

3 Theoretical framework and model specification

Per capita income and relative pricing, according to Naudé and Saayman (2005) and Lv and Xu (2017) are two variables that influence tourist demand. According to classical theory, demand is influenced by relative price and income. Individual income positively correlates with tourist demand, whereas relative prices

TABLE 1 Proxy measures of research variables.

Variable	Notation	Proxy	Reference	Source
Tourism development	TOR	International tourism, receipts (current US\$)	Osinubi et al. (2021)	
Good governance	GG	Government effectiveness	Qamruzzaman (2021); Yang et al. (2021); ALI et al. (2022); Qamruzzaman (2022b)	WGI
Globalization	GLO	Globalization index	Kearney and Policy (2006); Ahmed and Le. (2020); Aluko et al. (2021)	KOF Index
Environmental quality	EQ	Co2 emission per capital	Adebayo (2022); Adebayo et al. (2022)	WDI
Financial development	FD	Financial development index		IMF
Foreign direct investment	FDI	FDI inflows as a % of GDP		WDI

(as measured by the overall price level) negatively correlate with tourist demand. Tourist demand is estimated using the log of tourism revenues (Alola et al., 2019; Awosusi et al., 2022), relative prices are approximated using inflation, and individual income is represented by GDP per capita. The relationship is explained in Eq. 1.

$$\text{TOR}|\text{GDP, INF} \quad (1)$$

To account for the effects of other interesting variables, the study re-specifies Eq. 1 into Eq. 2 with the inclusion of good governance, globalization, and environmental quality. The motivation of the study was to explore the impact of good governance, globalization, and environmental quality on tourism development in BRIC for the period 1990–2021. For empirical assessment, the generalized relations can be exhibited as follows.

$$\text{TOR}|\text{GG, UR, EQ,} \quad (2)$$

where TOR stands for tourism development, GG exhibits good governance, UR explains urbanization, and EQ stands for environmental quality. Apart from the target variables, the study considered a list of control variables, that is, economic growth (Y), financial development (FD), and financial openness (FDI). Eq. 1 can be reproduced with the inclusion of control variables in the following manner.

$$\text{TOR}|\text{GG, GLO, EQY, FD, FDI.I.} \quad (3)$$

The variables are transformed with a natural log before target model estimation (Andriamahery and Qamruzzaman, 2022; Xia et al., 2022). After transformation, the baseline target model can be rewritten in the following ways.

$$\text{TOR}_i = \mu_1 + \beta_1 \text{GG}_i + \beta_2 \text{GLO}_i + \beta_3 \text{EQ}_i + \beta_4 \text{Y} + \beta_5 \text{FD}_i + \beta_6 \text{FDI}_i + \epsilon_i \quad (4)$$

The long-run coefficients can be addressed by the value of β_1 to β_6 . The value of μ_1 explains the constant term in the

equation. The measurement of each variable is displayed in Table 1.

3.1 Estimation strategy

3.1.1 Unit root test

An appropriate econometric technique section is appropriately guided by the research variable selection and their inherent properties; thus, the application of the stationary test has become one of the pre-assessment in the literature. We have considered several unit root tests following the ADF test offered by Dickey and Fuller (1979), the P–P test familiarized by Phillips and Perron (1988), the GF-DLS test following Elliott et al. (1996), and the KPSS test introduced by Kwiatkowski et al. (1992a). The Ng–Perron unit root test was performed in this study (Ng and Perron, 2001). The results of the unit root test are displayed in error! Reference source not found.

3.1.2 Bayer–Hanck combined cointegration test

The study implemented the cointegration test by following the framework proposed by Bayer and Hanck (2013), commonly known as the combined cointegration test. The proposed cointegration test consists of four conventional tests of cointegration familiarized by Banerjee et al. (1998), Peter Boswijk (1994), Johansen (1991), and Engle and Granger (1987a) with the null hypothesis of a no-cointegration test, the following Fishers' equation is considered in deriving the test statistics for detecting long-run association.

$$\text{EG} - \text{JOH} = -2[\text{LN}(\text{PEG}) + \text{LN}(\text{PJOH})], \quad (5)$$

$$\text{EG} - \text{JOH} - \text{BO} - \text{BD} = -2[\text{LN}(\text{PEG}) - \ln(\text{PJPB}) + \ln(\text{PBO}) + \ln(\text{PBDM})], \quad (6)$$

where PBDM, PBO, PJOH, and PEG stand for the significance levels of Banerjee et al. (1998), Boswijk (1995), Johansen (1991), and Engle and Granger (1987) respectively.

TABLE 2 Null hypotheses for all three tests are defined as follows.

Co-integration test	Null hypothesis	Alternative hypothesis
F-bound test	$\gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = \gamma_5 = \gamma_6 = 0$	Any, $\gamma_1, \gamma_2, \gamma_3, \gamma_4, \gamma_5, \gamma_6 \neq 0$
T-test on lagged dependent variable	$\gamma_1 = 0$	$\gamma_1 \neq 0$
F-test on the lagged independent variable	$\gamma_2 = \gamma_3 = \gamma_4 = \gamma_5 = \gamma_6 = 0$	Any, $\gamma_2, \gamma_3, \gamma_4, \gamma_5, \gamma_6 \neq 0$

3.1.3 Autoregressive distributed lagged

The long-run association in the empirical literature has been implemented with several conventional cointegration tests such as [Engle and Granger \(1987b\)](#), [Johansen \(1998\)](#), and [Johansen-JuseliusJuselius \(1990\)](#); the proposed cointegration test demands research variables' unique order of integration, suggesting that the mixed order of integration that is I (0) or I (1) is not applicable. The prevailing limitation in conventional cointegration tests, in the process of mitigating the problem, [Pesaran et al. \(2001a\)](#) have familiarized the cointegration test with mixed order of variable integration which is commonly known as autoregressive distributed lagged (ARDL). Since then, the ARDL approach has been extensively used in investigating long-run associations in empirical studies ([Qamruzzaman and Jianguo, 2018](#); [Qamruzzaman and Karim, 2020a](#); [Qamruzzaman and Karim, 2020b](#); [Qamruzzaman et al., 2020](#)). ARDL estimation possesses certain benefits over traditional cointegration tests, including 1) efficient estimation regardless of the study's sample size ([Ghatak and Siddiki, 2001](#); [Rehman et al., 2021](#); [Li and Qamruzzaman, 2022a](#); [Qamruzzaman, 2022b](#); [Xia et al., 2022](#)), 2) capability of handling mixed-order variable integration, and model stability and efficiency can be obtained by selecting appropriate lagged specifications ([Pesaran et al., 2001a](#); [Faruqui et al., 2015](#); [Ferdousi and QamruzzamanExport, 2017](#); [Ahmad et al., 2022](#)), and 3) unbiased estimation for both long-run and short-run elasticity ([Banerjee et al., 1993](#)).

Following [Pesaran et al. \(2001a\)](#), the generalized ADRL model for the study was considered for detecting both long-run and short-run coefficients by performing the following equation.

$$\begin{aligned} \Delta \ln TOR_t = & \alpha_0 + \sum_{i=1}^n \mu_1 \Delta \ln TOR_{t-i} + \sum_{i=0}^n \mu_2 \Delta \ln GLO_{t-i} \\ & + \sum_{i=0}^n \mu_3 \Delta \ln GG_{t-i} + \sum_{i=0}^n \mu_4 \Delta \ln EQ_t + \sum_{i=0}^n \mu_5 \Delta \ln FDI_{t-i} \\ & + \sum_{i=0}^n \mu_6 \Delta \ln FDI_{t-i} + \gamma_1 \ln TOR_{t-1} + \gamma_2 \ln GLO_{t-1} \\ & + \gamma_3 \ln GG_{t-1} + \gamma_4 \ln EQ_{t-1} + \gamma_5 \ln FDI_{t-1} + \gamma_6 \ln FDI_{t-1} \\ & + \omega_{1t} \end{aligned} \quad (7)$$

where Δ indicates differencing of variables, while ω_{1t} is the error term (white noise), and (t-1) is for the lagged

period, and is the long-run coefficient. Based on linear ARDL 11, the long-run coefficient to be available from γ_1 to γ_6 and short-run coefficients to be obtained from μ_1 to μ_6 from each empirical model estimation. Long-run association between variables to be tested following the F-test ([Pesaran et al., 2001a](#)) and the *t*-test on the lagged level of the dependent variable as suggested by and another additional F-test on the lagged levels of the independent variable(s) as suggested by [McNown et al. \(2018\)](#).

In the ARDL, according to [Pesaran et al. \(2001b\)](#), ([Pesaran et al. \(1999\)](#)), the bound testing approach is F-statistics which is established to determine the combined significance of the coefficients on the level. For the lagged dependent variables, the second test is a *t*-test. Under the null hypothesis, the statistics exhibit a nonstandard distribution because no level connection exists regardless of whether the regressors are I (0) or I. (1). However, reporting the F-test statistic for the overall test and the *t*-test statistic for a delayed dependent variable was inadequate for the ARDL test. To avoid the degenerate case, [McNown et al. \(2018\)](#) suggested a second *t*-test or F-test on the lagged independent variables in addition to the ARDL test used by [Pesaran et al. \(2001a\)](#). The use of all three criteria was required to differentiate between cointegration and degenerate instances.

[Pesaran et al. \(2001a\)](#) and [Sam et al. \(2019\)](#) presented two sets of asymptotic critical values, one for I (1) regressors and another for I (0) regressors. If the F-test statistic's value was less than the lower bound critical value or the *t*-test statistic's absolute value was less than the absolute lower bound critical value, the null hypothesis of "no long-run connection" could not be rejected. This indicated that there was no long-run connection between the variables. By contrast, if the F-test statistic's value exceeded the upper limit critical value or the *t*-test statistic's absolute value exceeded the upper bound critical value, the null hypothesis may be rejected ([Meng et al., 2021](#); [Miao and Qamruzzaman, 2021](#); [Zhang et al., 2021](#)). This indicated the existence of long-run connections between the variables. Finally, if the test statistic's value was neither less than nor higher than the two critical values, indicating that the value lay between the two critical values,

TABLE 3 Unit root test.

	At level				After first difference			
	ADF	GF-DLS	PP	KPSS	ADF	GF-DLS	PP	KPSS
For Brazil								
TOR	-2.29	-2.2614	-1.8734	0.5903***	-9.4329***	-6.1187***	-5.2914***	0.0189
GG	-2.0262	-2.0949	-1.3679	0.6776***	-5.2991***	-9.0623***	-7.247***	0.0209
EQ	-0.7966	-0.9151	-0.4382	0.9026***	-6.6663***	-6.8835***	-7.4367***	0.0189
UR	-2.3599	-0.3252	-2.1706	0.7873***	-8.9086***	-5.7118***	-9.4576***	0.0192
FD	-2.3815	-0.2782	-1.142	0.6756***	-6.6163***	-6.2132***	-7.4502***	0.021
FDI	-1.5889	-2.2768	-0.6346	0.67***	-9.5224***	-8.2706***	-5.7601***	0.0196
For Russia								
TOR	-2.2702	-2.4654	-2.456	0.6807***	-7.7372***	-5.5478***	-9.3409***	0.0206
GG	-0.6436	-1.788	-1.7278	0.702***	-6.2066***	-8.856***	-9.1647***	0.0202
EQ	-2.2853	-2.0228	-0.9555	0.8901***	-8.5751***	-9.5383***	-9.2377***	0.019
UR	-1.5063	-1.378	-0.5517	0.7243***	-9.0376***	-8.1289***	-6.2837***	0.0213
FD	-2.3633	-2.4123	-2.5343	0.6246***	-5.9506***	-8.1115***	-5.4072***	0.0193
FDI	-0.8264	-0.3602	-2.4633	0.7079***	-6.4588***	-6.0314***	-9.0069***	0.0195
For India								
TOR	-1.2015	-1.8505	-1.584	0.9283***	-9.1003***	-7.1956***	-5.5958***	0.0189
GG	-1.3475	-1.1506	-2.4761	0.931***	-5.911***	-9.1125***	-9.4654***	0.0191
EQ	-0.6678	-1.6429	-1.2221	0.8725***	-7.6846***	-9.0465***	-7.495***	0.0209
UR	-1.7759	-1.4134	-0.2873	0.5968***	-6.4197***	-5.7157***	-9.5703***	0.0204
FD	-1.0198	-2.4177	-1.237	0.634***	-7.7372***	-7.4705***	-8.6441***	0.0196
FDI	-1.4756	-1.7166	-0.8546	0.8489***	-5.7846***	-6.7779***	-8.2887***	0.0191
For China								
TOR	-1.7863	-0.5675	-2.4948	0.6686***	-7.7155***	-9.0693***	-8.0102***	0.0216
GG	-0.7506	-0.3815	-0.64	0.7074***	-7.9964***	-8.1678***	-8.6933***	0.021
EQ	-1.1701	-1.6725	-2.2512	0.751***	-6.822***	-8.5282***	-7.4636***	0.0197
UR	-1.5645	-1.0466	-2.0859	0.6649***	-8.0318***	-6.6971***	-7.2047***	0.0204
FD	-0.7907	-2.3475	-1.4991	0.7962***	-9.0298***	-8.7549***	-8.4969***	0.0206
FDI	-1.2339	-0.4035	-1.3597	0.7699***	-7.8858***	-8.1102***	-9.3555***	0.0212

Note: the superscript ***/**/* explain the significant level at a 1%, 5% and 10% respectively.

the conclusion about the long-run associations between the variables was ambiguous (Qamruzzaman and Ferdaous, 2014; Qamruzzaman, 2015; Qamruzzaman and Ferdaous, 2015; Qamruzzaman and Jianguo, 2017). For hypothesis see Table 2.

The study implemented the following equation with error correction terms to capture the short-run dynamics.

$$\Delta \ln TOR_t = \alpha_2 + \sum_{i=1}^n \beta_1 \Delta \ln TOR_{t-i} + \sum_{i=0}^n \beta_2 \Delta \ln GLO_{t-i} + \sum_{i=0}^n \beta_3 \Delta \ln GG + \sum_{i=0}^n \beta_6 \Delta \ln EQ_t + \sum_{i=0}^n \beta_7 \Delta \ln FD_{t-i} + \sum_{i=0}^n \beta_7 \Delta \ln FDI_{t-i} + \rho ECT_{t-1} + \omega_{it}. \quad (8)$$

We used a variety of diagnostic tests. First, we used the Harvey test to see whether the residuals of the enhanced ARDL model were heteroscedastic. Second, we used the Breusch–Godfrey serial correlation LM test to see whether the residuals were serially correlated. Third, we utilized the Ramsey RESET test as a model specification test. Fourth, we used the Jarque–Bera normality test to determine the normality of the model residuals. Finally, we checked for model stability using the cumulative sum (CUSUM) and CUSUM of square tests.

3.1.4 Nonlinear autoregressive distributed lagged

The study considered a nonlinear framework following Shin et al. (2014) empirical assessment for detecting the asymmetric impact of economic policy uncertainty and financial inclusion on remittances. For gauging the asymmetric effects of environmental quality (EQ), good governance (GG), and globalization (GLO) on tourism development (TOR), the following generalized equation is to be implemented:

$$TOR_t = (\pi^+ EQ_{1,t}^+ + \pi^- EQ_{1,t}^-) + (\beta^+ GG_{1,t}^+ + \beta^- GG_{1,t}^-) + (\gamma^+ GLO_{1,t}^+ + \gamma^- GLO_{1,t}^-) + \delta_t X_t + \varepsilon_t, \quad (9)$$

where π^+ , π^- , β^+ , β^- , and γ^+ , γ^- stand for the long-run asymmetric coefficient of environmental quality, good governance, and globalization. The asymmetric shock of independent variables can be derived in the following manner.

$$\begin{cases} POS(EQ)_{1,t} = \sum_{k=1}^t \ln EQ_k^+ = \sum_{k=1}^t \max(\Delta \ln EQ_k, 0) & POS(GG)_{1,t} = \sum_{k=1}^t \ln GG_k^+ = \sum_{k=1}^t \max(\Delta \ln GG_k, 0) \\ NEG(EQ)_t = \sum_{k=1}^t \ln EQ_k^- = \sum_{k=1}^t \min(\Delta \ln EQ_k, 0) & NEG(GG)_t = \sum_{k=1}^t \ln GG_k^- = \sum_{k=1}^t \min(\Delta \ln GG_k, 0) \end{cases}$$

$$POS(GLO)_{1,t} = \sum_{k=1}^t \ln GLO_k^+ = \sum_{k=1}^t \max(\Delta \ln GLO_k, 0),$$

$$NEG(GLO)_t = \sum_{k=1}^t \ln GLO_k^- = \sum_{k=1}^t \min(\Delta \ln GLO_k, 0).$$

Now, Eq. 9, transformed into asymmetric long-run and short-run coefficient assessment as follows:

$$\begin{aligned} \Delta TOR_t = & \partial U_{t-1} + (\pi^+ EQ_{1,t-1}^+ + \pi^- EQ_{1,t-1}^-) + (\beta^+ GG_{1,t-1}^+ + \beta^- GG_{1,t-1}^-) + (\gamma^+ GLO_{1,t-1}^+ + \gamma^- GLO_{1,t-1}^-) + \delta X_{1,t-1}^* \\ & + \sum_{j=1}^{m-1} \lambda_j \Delta TOR_{t-j} + \sum_{j=1}^{n-1} (\pi^+ \Delta EQ_{1,t-1}^+ + \pi^- \Delta EQ_{1,t-1}^-) \\ & + \sum_{j=1}^{n-1} (\mu^+ \Delta GG_{1,t-1}^+ + \mu^- \Delta GG_{1,t-1}^-) \\ & + \sum_{j=0}^{m-1} (\beta^+ \Delta GLO_{1,t-1}^+ + \beta^- \Delta GLO_{1,t-1}^-) + \sum_{j=0}^{m-1} \mu X_{1,t-1}^* + \varepsilon_t. \end{aligned} \quad (10)$$

A standard Wald test with a null symmetry hypothesis is implemented to detect long-run and short-run asymmetry. Only the insignificant test statistics will confirm the asymmetric association in the long and short runs. Furthermore, the asymmetric long-run cointegration to be assessed by following F-bound testing, joint primality test, and tBDM test, the higher test statistics relative to the critical value will confirm asymmetric cointegration in the empirical model.

4 Model estimation and interpretation

Empirical estimation with time series data needed to be confirmed with an elementary assessment of the order of integration assessed by implementing the stationary test. Following the existing literature, the study has performed unit root tests by following the ADF test (Dickey and Fuller, 1979), GF-DLS test (Elliott et al., 1996), PP test (Phillips and Perron, 1988), and KPSS test (Kwiatkowski et al., 1992b). The results of the unit root test are displayed in Table 3. Referring to the test statistics, it is apparent that all the variables are stationary after the first difference, and none of the variables are exposed to stationary after second-order differentiation, which is desirable for robust econometric assessment.

4.1 Bayer–Hanck cointegration test

Nest's study has implemented the newly offered cointegration test, widely known as the combined cointegration test, introduced by Bayer and Hanck (2013). Table 4 shows the long-run association test results with all five possible models. Compared to the test statistics and critical value at a 5% significance level, it is revealed that the rejection of the null hypothesis is no cointegration. The conclusion has been supported by both test statistics derived from EG-JOH and EG-JOH-BO-BDM. Once the long-run association has been established, we move to assess the elasticity of globalization, good governance, and environmental quality on tourism development in BIRC nations through linear and nonlinear assessments in the following section.

4.2 Empirical model estimation with autoregressive distributed lagged

The result of long-run cointegration with the ARDL framework is displayed in Table 5. Taking into account the test statistics of $F_{overall}$, t_{DV} , and F_{IDV} , it is manifested that the null hypothesis of no-cointegration has been rejected; alternatively, the long-run association between tourism development, environmental quality, globalization, good

TABLE 4 Results of combined cointegration test.

EG-JOH	Brazil	Russia	India	China	CV
TOR EQ	13.923	14.156	13.548	13.046	11.229
TOR EQ, GG	11.175	11.068	11.099	11.06	10.895
TOR EQ, GG, and GLO	10.759	10.837	11.165	11.355	10.637
TOR EQ, GG, GLO, and FDI	10.954	10.894	10.896	10.865	10.576
TOR EQ, GG, GLO, FDI, and FD	10.625	10.543	10.543	10.672	10.419
EG-JOH-BO-BDM					
TOR EQ	32.386	30.676	29.158	32.461	21.931
TOR EQ, GG	26.665	23.429	27.026	24.167	21.106
TOR EQ, GG, and GLO	21.991	22.598	22.127	23.314	20.486
TOR EQ, GG, GLO, and FDI	21.087	21.016	20.879	21.883	20.143
TOR EQ, GG, GLO, FDI, and FD	20.895	20.882	20.846	20.883	19.888

TABLE 5 Results of long-run cointegration.

		Brazil	Russia	India	China	
Tor GLO, GG, EQ, FD, FDI	$F_{overall}$	11.095***	9.939***	15.254***	9.737***	
	t_{DV}	-5.391***	-6.931***	-6.817***	-6.254***	
	F_{FDV}	10.408***	10.058***	8.847***	6.313***	
Critical value: $K = 5$		1%	5%		10%	
	I (0)	I (1)	I (0)	I (1)	I (0)	I (1)
Pesaran, Shin and Smith (Banerjee et al., 1998)	5.095	6.77	3.673	5.002	3.087	4.277
Narayan (Ahmad et al., 2022)	-3.96	-5.13	-3.41	-4.52	-3.13	-4.21
Sam, McNown and Goh (Qamruzzaman and Karim, 2020b)	3.58	5.91	2.46	4.18	2	3.47

Note: the superscript ***/**/* explain the significant level at a 1%, 5% and 10% respectively.

governance, foreign direct investment, and financial development has been established. The conclusion of the long-run association is valid for all four sample countries. Now we are moving to gauge the elasticity both in the long-run and short-run.

The results of long-run and short-run coefficients are displayed in Table 6, where panel-A deals with long-run coefficients and panel-B deals with short-run coefficients and the residual diagnostic test is displayed in panel-C.

Referring to long-run assessment, the study documented the negative and statistically significant association between environmental quality and tourism development in Brazil (a coefficient of -0.1298), Russia (a coefficient of -0.1749), India (a coefficient of -0.1837), and China (a coefficient of -0.1447). The study findings suggest that environmental disequilibrium has created adversity in tourism development. More precisely, a 10% additional carbon emission in the environment can adversely cause the present trend in tourism development by 1.298% in Brazil, 1.749% in Russia, 1.837% in India, and 1.447% in China, respectively. Our study findings align with existing literature (Jermisittiparsert, 2019). In the case of short-run assessment, the

study confirmed the adverse connection between environmental quality and tourism development in Brazil (a coefficient of -0.0603), Russia (a coefficient of -0.0593), India (a coefficient of -0.068), and China (a coefficient of -0.0516).

In the case of globalization, the study documented a positive and statistically significant linkage to tourism development in the selected BRIC nations. In particular, a 10% improvement in economic and financial global integration can intensify tourism development by 1.585% in Brazil, 1.651% in Russia, 0.325% in India, and 0.558% in China, respectively. The study findings postulate that economic internationalization has emerged as a boost to tourism industry development. In the short run, globalization's impact has been positive but statistically significant in all nations except Brazil (a coefficient of 0.0517). The study documented that good governance plays a critical role in tourism development, indicating the positive and statistically significant tie between them in BRIC nations. Specifically, a 1% development in governmental effectiveness increases tourism development in Brazil by 0.0624%, in Russia by 1.931%, in India by 1.495%, and by 1.833% in China, respectively.

TABLE 6 Long-run and short-run coefficients: ARDL estimation.

	Brazil	Russia	India	China
Panel-A: long-run coefficient				
EQ	−0.1298 (0.0268) [−4.8448]	−0.1749 (0.0407) [−4.2879]	−0.1837 (0.0798) [−2.3024]	−0.1447 (0.081) [−1.7853]
GLO	0.1585 (0.0324) [4.8837]	0.1651 (0.0473) [3.489]	0.0325 (0.0097) [3.3468]	0.0558 (0.0161) [3.4633]
GG	0.0624 (0.0085) [7.3449]	0.1931 (0.0182) [10.592]	0.1495 (0.0178) [8.3992]	0.1833 (0.0996) [1.8403]
FDI	0.1602 (0.0204) [7.8301]	0.121 (0.0269) [4.4933]	0.1042 (0.0481) [2.1657]	0.0959 (0.0182) [5.2598]
FD	−0.3257 (0.04) [−8.1289]	0.0941 (0.0153) [6.1304]	0.0859 (0.0511) [1.6808]	0.1796 (0.0581) [3.0877]
C	25.554 (0.6161) [41.4709]	7.7075 (0.4512) [17.0822]	−2.3454 (0.533) [−4.4002]	39.0718 (7.9084) [4.9405]
Panel-C: short-run coefficients				
ΔEQ	−0.0603 (0.0331) [−1.8212]	−0.0593 (0.0331) [−1.8212]	−0.068 (0.0326) [2.0877]	−0.0516 (0.0914) [−0.5646]
ΔGLO	0.0517 (0.0049) [10.4342]	0.0521 (0.0495) [1.0434]	0.0245 (0.0439) [0.0557]	0.0183 (0.0468) [0.3923]
ΔGG	0.0139 (0.0026) [5.2226]	0.0179 (0.0066) [2.0859]	0.0787 (0.0498) [1.5799]	0.0436 (0.0159) [2.7273]
ΔFDI	−0.0292 (0.0014) [−12.3453]	−0.0252 (0.0104) [−2.796]	0.0745 (0.0586) [1.2699]	0.0377 (0.0356) [1.0572]
ΔFD	0.1031 (0.0154) [6.6892]	0.0316 (0.0154) [2.054]	0.0137 (0.0172) [0.7976]	0.0039 (0.0045) [0.863]
C	−0.5891 (0.082) [−7.1789]	0.0919 (0.0207) [4.4372]	−0.3125 (0.0255) [−12.2469]	−0.0175 (0.0079) [−2.2044]
Panel-C: residual diagnostic test				
χ^2_{Auto}	0.581	0.776	0.867	0.718
χ^2_{Het}	0.676	0.779	0.638	0.748
χ^2_{Nor}	0.688	0.718	0.574	0.667
χ^2_{RESET}	0.562	0.844	0.599	0.816

Referring to control variables' impact on tourism development in the long-run (short-run); according to coefficients, it is apparent that foreign direct investment has a positive (negative) association with tourism development. In the case of financial development, the study established a positive (positive) tie to tourism development in BRIC nations. The study has performed several residual diagnostic tests to confirm the model's efficiency and consistency (as shown in panel-C). Referring to test statistics from a diagnostic test, and the model is free from serial correlation, residuals are normally distributed, have no heteroskedasticity, and are internally consistent in estimation. Furthermore, the CUSUM test and CUSUM of the square test reveal the model construction stability.

The next study extended the elasticity assessment with the implementation of asymmetric ARDL, including the asymmetric shocks of good governance, environmental quality, and globalization. The results of the nonlinear assessment are displayed in Table 7, which include asymmetric cointegration results in panel-A, the long-run coefficients in panel-B, the short-run coefficient in panel-C, and the residual diagnostic results in panel-D, respectively.

Long-run cointegration with the asymmetric framework, according to the test statistics derived from $F_{overall}$, t_{DV} , and F_{IDV} , has confirmed the rejection of the null hypothesis, implying the long-run cointegration in the empirical association. Once the long-run asymmetric cointegration has revealed, the study moves in evaluating the asymmetric effects of globalization, good governance, and environmental quality on tourism development.

Referring to asymmetric long-run coefficients; as shown in panel-B in Table 7. Environmental quality measured by carbon emission has revealed a negative and statistically significant linkage to tourism development in BRIC nations. More precisely, environmental degradation, which is a 10% augmentation of carbon emission in the environment, results in adverse effects on the present state of tourism development in Brazil by 1.658%, Russia by 1.258%, India by 1.886%, and China by 1.544%. However, a 10% environmental development through carbon reduction, according to coefficient, it is unveiled that environmental quality improvement will result in tourism development in Brazil by 0.551%, Russia by 0.851%, India by 0.769%, and China by 0.731%. In the short-run, the positive shock in environmental quality was negative and statistically significant, indicating that environmental degradation discourages international tourists from visiting an economy

TABLE 7 Results of nonlinear ARDL assessment.

	Brazil	Russia	India	China
Panel-A: asymmetric long-run cointegration				
$F_{overall}$	14.144***	10.949***	9.123***	12.399***
t_{DV}	-7.112***	-6.484***	-5.387***	-6.647***
F_{IDV}	7.94***	9.065***	6.795***	8.265***
Panel-A: long-run coefficient				
EQ_POS	-0.1658 (0.0891) [-1.8599]	-0.1258 (0.0891) [-1.8599]	-0.1886 (0.0384) [-4.9075]	-0.1544 (0.0383) [-4.0264]
EQ_NEG	-0.0551 (0.0265) [-2.0728]	-0.0851 (0.0265) [-2.0728]	-0.0769 (0.0467) [-1.6468]	-0.0731 (0.0016) [-45.6901]
GG_POS	0.0716 (0.0175) [4.0892]	0.1716 (0.0751) [2.2837]	0.0831 (0.0406) [2.0454]	0.0989 (0.0272) [3.6292]
GG_NEG	0.0651 (0.0293) [2.2157]	0.1651 (0.0893) [1.8471]	0.0527 (0.0197) [2.6721]	0.1265 (0.0559) [2.2624]
GLO_POS	0.2253 (0.0787) [2.8605]	0.1253 (0.0487) [2.8605]	0.1885 (0.0414) [4.5506]	0.0333 (0.0141) [2.3583]
GLO_NEG	0.0923 (0.0427) [2.1615]	0.0999 (0.0427) [2.3401]	0.1178 (0.0812) [1.451]	0.0468 (0.0265) [1.7651]
FD	0.2247 (0.0206) [10.8637]	0.0824 (0.0206) [3.9871]	0.0929 (0.0253) [3.6632]	0.0616 (0.0357) [1.725]
FDI	0.1072 (0.05) [2.1434]	0.1072 (0.05) [2.1434]	0.079 (0.0329) [2.4005]	0.1415 (0.0514) [2.7526]
C	15.2656 (0.321) [47.5561]	15.2656 (0.321) [47.5561]	-8.5077 (0.3804) [-22.3634]	8.6203 (0.857) [10.0583]
Panel-C: short-run effects				
EQ_POS	-0.0497 (0.0076) [-6.4727]	-0.0436 (0.0134) [-3.2384]	-0.0999 (0.033) [-3.0195]	-0.064 (0.0465) [-1.3775]
EQ_NEG	-0.0301 (0.6743) [-0.0446]	-0.1026 (0.0751) [-1.3647]	-0.0332 (0.0194) [-1.7065]	-0.0335 (0.0518) [-0.6465]
GG_POS	0.0417 (0.0075) [5.5013]	0.0497 (0.0479) [1.0375]	0.0395 (0.0421) [0.9371]	-0.0883 (0.0443) [-0.5488]
GG_NEG	0.0042 (0.0012) [3.4653]	0.0343 (0.0051) [6.7257]	0.074 (0.0296) [2.4996]	0.0309 (0.0742) [0.417]
UR_POS	-0.04 (0.0196) [-2.0406]	0.0497 (0.0168) [2.9584]	-0.0195 (0.0013) [-14.3438]	0.0597 (0.0225) [2.6491]
UR_NEG	0.0436 (0.0034) [12.5882]	0.043 (0.0074) [5.7832]	0.0992 (0.0045) [21.9186]	0.0902 (0.0277) [3.2551]
FD	-0.026 (0.0027) [-9.452]	0.0744 (0.0275) [2.7001]	0.0436 (0.0346) [1.2588]	0.0131 (0.006) [2.1827]
FDI	0.1072 (0.0479) [2.2382]	-0.0206 (0.0634) [-0.3261]	-0.026 (0.0075) [-3.4597]	0.0772 (0.004) [19.1718]
ect.	-0.343 (0.0605) [-5.6686]	-0.4105 (0.0449) [-9.1315]	-0.1497 (0.0479) [-3.1247]	-0.323 (0.0187) [-17.2552]
Panel-D: Wald and residual diagnostic test				
W_{LR}^{EQ}	5.114	9.534	5.131	8.068
W_{LR}^{GG}	5.203	13.259	11.842	13.545
W_{LR}^{GLO}	3.678	11.178	5.916	10.061
W_{ER}^{EQ}	11.136	12.929	3.898	13.501
W_{ER}^{GG}	8.166	13.427	8.768	8.091
W_{SR}^{GLO}	5.934	11.546	3.146	12.818
χ^2_{Auto}	0.833	0.621	0.644	0.613
χ^2_{Het}	0.622	0.743	0.488	0.824
χ^2_{Nor}	0.829	0.711	0.812	0.755
χ^2_{RESET}	0.606	0.506	0.867	0.579

Note: the superscript ***/**/* explain the significant level at a 1%, 5% and 10% respectively.

with a higher carbon concentration. The study postulated that environmental quality has acted as an incubator role in tourism development, suggesting environmental hazard and ecological

imbalance have created negative propaganda and discouraged international visitors, which eventually causes an adverse influence on tourism development.

TABLE 8 Toda–Yamamoto causality test ($k = 3$).

	TOR	GG	EQ	GLO	FDI	FD	Causality
Panel-A: for Brazil							
TOR	—	2.896	10.778***	3.172	7.944*	9.031**	TOR→GG; EQ←→TOR; TOR→GLO; FDI←→TOR; FD←→TOR; GG→EQ; GLO→GG; GG→FDI] GG→FD; GLO←→EQ; FDI→EQ; FD→EQ; FDI←→GLO; FD←→GLO; FD←→FDI
GG	5.263*	—	4.028	6.183*	3.784	5.666	
EQ	10.276***	11.458***	—	11.747***	10.913***	6.135*	
	7.988*	4.306	10.117***	—	11.572***	9.738**	
GLO							
FDI	7.248*	7.467*	4.085	8.882**	—	7.477*	
FD	6.201*	8.974**	4.383	7.169*	12.718***	—	
Panel-B: for Russia							
TOR	—	6.643*	7.745*	4.387	10.399***	3.918	GG→TOR; EQ→TOR; FDI←→TOR; FD→TOR; GG→EQ; GG←→GLO; GG←→FD; GLO→EQ; FDI←→EQ; FD→EQ; GLO→FDI; FDI←→GLO
GG	5.871	—	4.524	8.235**	2.992	6.085*	
EQ	2.913	9.935**	—	8.607**	9.326**	5.312	
	9.085**	11.898***	5.115	—	5.571	11.691***	
GLO							
FDI	6.211*	4.19	10.72***	6.918*	—	5.702	
FD	12.218***	9.564**	10.157***	9.25**	4.805	—	
Panel-C: for India							
TOR	—	11.895***	6.662*	2.699	7.09*	13.062***	GG→TOR; TOR←→EQ; TOR→GLO; FDI←→TOR; FD←→TOR; GG→EQ; GLO←→GG; FDI←→GG; FD←→GG; GLO←→EQ; FD→EQ; GLO→FDI; FD→GLO; FDI←→FD
GG	3.075	—	4.474	9.059**	9.713**	9.757**	
EQ	9.178**	12.84***	—	8.136**	3.229	6.27*	
	10.054***	6.778*	6.735*	—	5.245	7.417*	
GLO							
FDI	8.154**	12.365***	3.513	6.477*	—	12.195***	
FD	9.951**	6.818*	3.742	2.649	7.201*	—	
Panel-D: for China							
TOR	—	13.178***	6.751*	7.818*	12.143***	8.968**	GG←→TOR; EQ←→TOR; GLO←→TOR; FDI→OR; TOR←→FD; GG→EQ; FDI←→EQ; FD→EQ; FDI←→GLO; GLO→FD; FD→FDI
GG	11.751***	—	3.317	3.709	4.877	11.783***	
EQ	8.909**	5.457	—	3.438	11.749***	2.691	
	12.95***	12.635***	11.011***	—	6.108*	2.672	
GLO							
FDI	3.405	5.04	10.06***	8.94**	—	6.678*	
FD	7.228*	6.727*	8.554**	12.835***	5.262	—	

Note: the superscript ***/**/* explain the significant level at a 1%, 5% and 10% respectively.

The study documented asymmetric shocks of good governance that have a positive (negative) variation and statistically significant relationship with tourism development in Brazil with a coefficient of 0.0716 (0.0651), Russia with a

coefficient of 0.1716 (0.1651), India with a coefficient of 0.0831 (0.0527), and China with a coefficient of 0.0989 (0.1265). In particular, the study findings suggest that a 10% positive (negative) innovation in good governance may result in

tourism development accelerated (degraded) in Brazil by 0.716% (0.651%), Russia by 1.716% (1.651%), India by 0.831% (0.527%), and China by 0.989% (1.265%), respectively. In the short run, positive shocks in good governance have revealed positive and statistically significant ties with tourism development in Russia, India, and China, but positive and statistically significant connections are documented for Brazil. Moreover, the negative shocks in good governance have positively connected to tourism development in BRIC nations. Considering the asymmetric coefficients of good governance on tourism development, it is undoubtedly confirmed that governmental effectiveness ensures economic and financial stability for fostering equitable development, eventually supporting tourism development in the long and short runs.

Referring to globalization effects on tourism development, the study has documented positive and statistically significant linkage, suggesting the positive (negative) variation in global integration will result in acceleration (declination) in the tourism development in BRIC nations. In particular, a 10% change in globalization will produce positive (adverse) effects on tourism development in Brazil by 2.253% (0.923%), Russia by 1.253% (0.999%), India by 1.885% (1.178%), and China by 0.333% (0.468%), respectively. Furthermore, in the short run, the study established that positive shock in globalization was positively tied to Russia (a coefficient of 0.0343) and China (a coefficient of 0.0597), whereas a negative association was revealed for Brazil (a coefficient of -0.04) and India (a coefficient of -0.0195). On the other hand, the negative variations unveiled positive and statistically significant ties to tourism development in BRIC nations. The study findings suggest the global economic integration.

The assessment of the asymmetric association between environmental quality, good governance, and globalization on tourism development in BRIC has been confirmed with the standard Wald test, and their results are displayed in panel-C. According to the test, statistics derived from the Wald test have found the rejection of the null hypothesis that is no-asymmetric relations. Alternatively, the Wald test confirmed the asymmetric association both in the long-run and short-run. Furthermore, the study has performed several residual diagnostic tests.

Next, the study implemented the causality test by following the non-granger causality framework offered by Toda. The causality test results are displayed in Table 8 and documented several directional associations among research variables. Focusing on the target variables, the study revealed feedback hypothesis holds in explaining the causality between environmental quality and tourism development [$EQ \leftarrow \rightarrow TOR$] in Brazil, India, and China, and good governance and tourism development [$GG \leftarrow \rightarrow TOR$] in India, and globalization and tourism development [$GLO \leftarrow \rightarrow TOR$] in China. Furthermore, the unidirectional causality runs from tourism to good governance [$TOR \rightarrow GG$] in Brazil, whereas

causality runs from good governance to tourism development [$GG \rightarrow TOR$] in Russia, India, and China. In the case of globalization to tourism development [$GLO \rightarrow TOR$], the study established unidirectional causal effects in India, while tourism led to globalization [$TOR \rightarrow GLO$] found in Brazil.

5 Discussion

The present study investigates the impact of globalization, good governance, and environmental quality on tourism development in BRIC nations with symmetric and asymmetric frameworks. Environmental quality, measured by the carbon emission into the environment, negatively affects tourism development. Alternatively, improving environmental quality through carbon reduction positively boosts tourism development in BRIC nations. The study finding has suggested that environmental adversity characterized by excessive heat, ecological imbalance, and natural resource destruction demotivated international tourist to visit that economy. According to long-run coefficients for environmental quality on tourism development, it is evident that a 10% reduction in carbon emission in the economy will result in tourism development by tourism development of 1.298% in Brazil, 1.749% in Russia, 1.837% in India, and 1.447% in China, respectively. Our study findings are in line with existing literature by Jermisittiparsert, 2019), Sajjad et al. (2014), and Suharyono and Digdowiseiso (2021). The relationship between air pollution and tourism may be investigated at local and macro levels. Based on a study of China residents in the United States and Australia, Becken et al. (2017) discovered that the perceived danger of air quality in China is adversely connected to travel intent and assessment of the destination. According to Peng and Xiao (2018), air pollution significantly negatively influences visitor happiness and a location's reputation. According to Deng et al. (2017), industrial gas emissions in Chinese provinces were highly and negatively connected with the worldwide inbound tourism industry. Xu and Reed (2017) linked China's low inbound tourism to the country's high levels of air pollution in a second study.

The study established a positive and statistically significant connection between globalization and tourism development in BRIC nations, which is valid for both symmetric and asymmetric assessment. According to coefficients, the study advocated that global economic and financial integration has played a critical role in tourism development with effective innovation in marketing activities, knowledge sharing, and infrastructural development. Because we live in a time of globalization, tourism, which represents a large share of the contemporary economy of the whole world, is unavoidably being enmeshed in such an overwhelming process, which is happening for several reasons. The worldwide flows of cash, information, and services within the tourist industry are likely to be substantially more frequent and intensive than most other businesses and economic sectors (Theuns, 2014). This is a result of the fact that engaging in

activities associated with international tourism inevitably involves transporting visitors across national boundaries, in addition to the required adjustments in space and time (Theuns, 2008).

For good governance, the study documented positive and statistically significant connections to BRIC nations' tourism development in the long and short-run assessments. Furthermore, the asymmetric shocks of good governance that is positive and negative variation have established positive and statistically significant interlinkage both in the long run and short run. Precisely, in the long run, a 10% positive (negative) innovation in good governance may result in tourism development accelerated (degraded) in Brazil by 0.716% (0.651%), Russia by 1.716% (1.651%), India by 0.831% (0.527%), and China by 0.989% (1.265%), respectively. In the short run, positive shocks in good governance have revealed positive and statistically significant ties with tourism development in Russia, India, and China, but positive and statistically significant connections are documented for Brazil. Moreover, the negative shocks in good governance have positively connected to tourism development in BRIC nations. Considering the asymmetric coefficients of good governance on tourism development, it is undoubtedly confirmed that governmental effectiveness ensures economic and financial stability for fostering equitable development, eventually supporting tourism development in the long and short runs. Our findings align with existing literature, for instance, Sou and Vinnicombe (2021), Xu et al. (2021). Existing literature has postulated that inefficient institutional quality, corruption, and political instability unmined tourism growth prospects in the long run, which eventually degraded equitable tourism-led economic growth (Del Monte and Papagni, 2001; de Vaal and EbbenInstitutions, 2011; Faheem et al., 2019; Andriamahery and Qamruzzaman, 2022; Xia et al., 2022; Zhuo and Qamruzzaman, 2022). The study of Sou and Vinnicombe (2021) advocated that good governance accelerates tourism development through the indirect channel that is governmental effectiveness and political stability which induces foreign capital flows into the economy for infrastructural development, and the tourism industry is one of the targeted industries. Thus, the presence of effective institutional quality, governmental effectiveness, and practices not only augments industrial development but also assists in sustainable economic progress. Furthermore, Osinubi et al. (2021) advocated that excessive corruption's absence of good governance has negatively tied to Nigeria's tourism development.

6 Conclusion and policy recommendation

The impact of tourism development has been extensively established in the literature, and on the other side, the key macro

determinants for tourism development has been investigated. However, the conclusive evidence focusing on the contributory factors for tourism development has yet to be revealed. The motivation of the study was to gauge the role of environmental quality, good governance, and globalization in tourism development in BRIC nations for the period 1990–2021. Exploring the fresh insight, the study has implemented both linear and nonlinear frameworks following Pesaran et al. (2001a) and Shin et al. (2014). The key summary findings are as follows.

Combined cointegration test statistics show a long-run association between EQ, GG, and GLO and tourism development in BRIC nations. Furthermore, the long-run association in the empirical estimation is established in both linear and nonlinear framework assessments. Referring to linear assessment, the study documented the positive and statistically significant linkage between good governance and globalization, implying that political stability, governmental effectiveness, and accountability have been revealed as boosting factors for tourism development. Moreover, global economic and financial integration opens a window for tourism development by inducing the economy's international tourism. On the other hand, environmental degradation, which is the carbon emission in the economy, adversely affects tourism development, indicating that the healthy and amicable ambiance positively triggers tourism development in the long run. According to the test statistics of the standard Wald test, it is obvious that there is an asymmetric association between explanatory variables such as EQ, GG, and GLO and tourism development in the long-run and short-run assessment. The directional causality test documented bidirectional causality in explaining the causality between environmental quality and tourism development [EQ $\leftrightarrow$ TOR] in Brazil, India, and China, good governance and tourism development [GG $\leftrightarrow$ TOR] in India, and globalization and tourism development [GLO $\leftrightarrow$ TOR] in China. Furthermore, the unidirectional causality runs from tourism to good governance [TOR $\rightarrow$ GG] in Brazil, whereas causality runs from good governance to tourism development [GG $\rightarrow$ TOR] in Russia, India, and China. In the case of globalization to tourism development [GLO $\rightarrow$ TOR], the study established unidirectional causal effects in India, while tourism led to globalization [TOR $\rightarrow$ GLO] found in Brazil.

On policy note, considering the empirical findings, the study reached the following suggestion for future development in the tourism sector.

1. According to the research findings, carbon emissions hinder the growth of the tourist industry in BRIC countries, both in the long and short terms. Alternately, it has been demonstrated that a decrease in carbon emissions as part of environmental development would result in a favorable acceleration in tourism growth. In light of this, it is recommended that environmental protection regulations be

formulated and effectively implemented to make the most of the potential for tourism growth.

2. Economic and financial openness offers economic accessibility by offering economic stability, which indicates effective and efficient governmental effectiveness. Furthermore, good governance has played a critical role in corruption reduction in the economy, which leads to long-term tourism development. Therefore, it is suggested that BRIC should ensure governmental effectiveness through institutional quality development, implying economic stability and progressive development in the tourism industry.
3. The opening up of economies and financial markets has been shown to have a major connection in the advancement of economies, due to the large contribution of other industries. The research findings indicated that globalization has a favorable connection to the expansion of tourism, which suggests that economic and financial globalization helps boost tourism. These findings were based on an estimate. According to the research findings, BRIC countries need to demonstrate that they can conduct effective and efficient financial intermediation to advance the current level of globalization. The research indicates that increased financial efficiency and intermediation led to increased capital flows and international commerce. In addition, domestic trade liberalization and foreign ownership involvement in the economy both favorably encourage globalization, leading to tourism growth.

The present study is not out of certain limitations; therefore, further development can initiate future research. First, the present study has considered the tourism receipts as a percentage of GDP as the proxies for tourism development; in the case of future studies, the proxy measure of tourism can be reinvestigated with international tourist arrivals and tourist expenditure. Second, the present study has considered carbon emission as the measure of environmental quality, so the further extension can be executed with the inclusion of air quality as a proxy of environmental quality, which is available in the literature.

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Data availability statement

Publicly available datasets were analyzed in this study. These data can be found here: World Bank database.

Author contributions

MQ: Introduction, methodology, and empirical model estimation; CG: Data accumulation, literature survey, first draft preparation, and final Preparation.

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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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Are environmental regulation tools effective? An analysis based on financial investment of entity enterprises

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Environmental regulation and economic development are consistent in the long run, but there are certain contradictions in the short term. Examining the characteristics of available environmental regulation tools and using them in a way that will align the interests of local governments and enterprises can improve environmental regulation and enhance green transformation and development. This study considers two general types of environmental regulation tools: negative punishment types and positive incentive types. Applying an intermediary effect model and the two-stage least squares method, a sample of Chinese A-share listed companies from 2007 to 2019 is used to test the impact of these different types of environmental regulation tools on the financial investment levels of entity enterprises. The mechanism through which these macro-environmental regulation tools function and the micro-enterprise heterogeneity factors that influence their impact are systematically studied. The results show that negative punishment type environmental regulation tools have a positive impact on the financial investment levels of entity enterprises, while positive incentive type environmental regulation tools inhibit financial investment levels. This impact is formed through managerial incentive mechanisms referred to as “whipping the fast ox” and “heavy rewards and light punishments.” Factors such as financing constraints, relocation costs, pollution levels, and enterprise scale have heterogeneous effects on these paths. Policy suggestions are offered based on the findings. This study makes a significant contribution to the literature by clarifying the channel through which environmental regulation influences micro-enterprise decision-making. It provides a theoretical basis and policy reference for local government officials as they address the conflict between economic growth and environmental protection in the short term. Moreover, the results offer long-term development decision-making ideas for shareholders and managers in the process of green transformation and upgrading of enterprises.

KEYWORDS

environmental regulation tools, negative punishment, positive incentive, entity enterprises, financial investment

1 Introduction

Sustainable development is currently a key global issue, and, for many countries, the contradiction between rapid economic growth and environmental carrying capacity is becoming increasingly deeper. Environmental degradation has a serious impact on sustainable development (Arslan et al., 2022; Wen et al., 2021). However, although they are the main producers of pollutants, enterprises usually lack the motivation to perform environmental governance activities (Arouri et al., 2012; Borghesi et al., 2015). Consequently, governments are compelled to encourage enterprises to participate in environmental governance by establishing emission indicators and providing cash and tax incentives to reduce environmental pollution at its source. Accordingly, governments worldwide are exploring environmental regulation systems that consider both environmental protection and economic development and issuing a series of policies related to sustainable development (Kirikkaleli and Adebayo, 2021; Mughal et al., 2022).

Most existing studies divide environmental regulation tools into three categories: command-type, public-participation-type, and market-incentive-type. Among these, command-type environmental regulation tools usually involve the government formulating a series of emission caps and emission reduction standards and directly intervening in enterprise environmental strategies through non-market measures such as administrative orders or coercion. Public-participation-type environmental regulation tools are used to supervise enterprise pollution control processes through informal systems, relying on public opinion, mass petitions, and other forms. The market-incentive-type environmental regulation tool is a method, in which the government actively guides enterprises to adjust production decisions in market-oriented ways, such as through tax cuts, incentives, and emissions trading (Xie et al., 2017). Various environmental regulation tools have certain effects. For example, Chen et al. (2020) believe that market-incentive-type environmental regulation tools have stronger environmental governance effects. Dong et al. (2022) believe that environmental taxes can reduce pollutant emissions. Langpap and Shimshack (2010) argue that public-participation-type regulation tools play a significant role in pollution control.

There are certain differences in how environmental regulation tools impact enterprise operation and transformation development, and academia has not yet formed a consensus. One view holds that there is a pressure mechanism; that is, environmental regulations exert certain pressure on enterprises and add environmental governance costs, leading to cost increases (Zhang et al., 2018), R&D stagnation (Zhou et al., 2020), and reduced investment (Silvia et al., 2017). To overcome the

stress stage, enterprises usually seek financing, production reduction, and other ways to increase income and reduce expenditure (Petroni et al., 2019) or migrate to areas with lower environmental regulation standards to form a pollution refuge (Mani and Wheeler, 1998). Another view proposes a compensation mechanism; that is, enterprises under environmental regulation may increase technological innovation and improve production efficiency to offset the increase in environmental protection expenditure costs (Qiaoxin, 2021).

Although previous studies have investigated the relationship between environmental regulation tools and business decision-making, research gaps remain. Existing studies have ignored the applicability of different types of environmental regulation tools, resulting in two opposite conclusions about the most effective regulatory mechanisms; some support the use of “pressure mechanisms,” while others favor “compensation mechanisms.” Additionally, past studies have focused on how environmental regulation impacts an enterprise’s choice of investment direction but have ignored the impact logic between the two. Enterprise investment decisions can be divided into financial investments and industrial operations. The mutual transformation of the two is essentially a choice of resource allocation and a change in efficiency (Li and Wenfeng, 2021). For example, Haijing et al. (2021) argue that environmental regulation places operational pressure on enterprises, making their profit-seeking motives more obvious and prompting them to improve their financial investment level. Maomao and Yanyan (2021) reached the opposite conclusion. They argue that the new Environmental Protection Law urges enterprises to transform and upgrade as soon as possible, while the improvement in the R&D level restrains the financial investment level. However, neither of these studies discuss the paths through which the laws influence enterprise behaviors.

This study’s objective is to resolve these key issues and fill the gap in existing research. First, it examines the impact of two different environmental regulation tools—“negative punishment” and “positive incentives”—on enterprise financial investments and discusses how various corporate characteristics, such as financing constraints, relocation costs, pollution levels, and firm size, affect these paths. Second, this study discusses the role of managerial incentive mechanisms in the path between environmental regulation and enterprise investment preferences and provides corresponding theoretical support. In view of this, this study takes Chinese A-share entity listed companies from 2007 to 2019 as its sample to conduct an empirical study that applies a fixed-effects panel regression model, the two-stage least squares method, and an intermediary effect model.

The results show that negative punishment environmental regulation tools have a positive impact on the financial investment levels of entity enterprises, while positive incentive

environmental regulation tools inhibit financial investment. Managerial incentive mechanisms of “whipping the fast ox” and “heavy rewards and light punishments” are the direct paths through which negative punishment environmental regulation tools act on the financial investment levels of entity enterprises. In contrast, positive incentive environmental regulation tools mainly act by alleviating cost pressures, obtaining tax cuts, and financial incentives. In addition, the sensitivity of different types of enterprises to environmental regulation tools differs and has a heterogeneous impact on the logical chain.

Our study contributes to both theory and literature, and the results have managerial implications. First, the study provides theoretical support for the two opposite conclusions of “pressure mechanisms” and “compensation mechanisms” produced by previous studies. From the perspective of enterprise financial investment, this study breaks down the relevant research on how environmental regulation impacts enterprise investment and discusses the effect of different corporate characteristics and applicability of environmental regulation tools. Second, it supplements the evidence of managerial incentive paths in terms of environmental regulation tool effectiveness, enriches the research on the transmission path between macro-environmental policy and micro-enterprise investment decision-making, and provides a certain theoretical basis and literature support for the relationship between environmental regulation and enterprise investment. Third, the results provide practical suggestions for local governments as they choose environmental protection policies and for enterprises in their decision-making processes, offering ideas conducive to the long-term development of shareholders and managers in the process of green transformation and development.

This study’s originality lies in its focuses on corporate behavior from the perspective of environmental regulation tool effectiveness, finding differences in the effectiveness of environmental regulation given various corporate characteristics. Second, it is one of a few studies to find the existence of a managerial incentive path between environmental regulation and enterprise behavior, showing that a managerial incentive mechanism plays an important role in the relationship between the two.

2 Hypotheses

Many scholars have studied the relationship between environmental protection and economic development and believe that the two are internally consistent in the long run.

However, in the short run, implementing inappropriate environmental regulation tools may negatively impact local economic growth and business decision-making. In the long run, implementing environmental policies can improve the level and potential of economic growth through health effects and R&D effects (Raffin, 2014; Dao and Edenhofer, 2018). However, during the tenure of local government officials, environmental constraints have been incorporated into the promotion competition system, forcing officials to choose between short-term and conflicting goals. Consequently, some mandatory and executive-ordered policies have been implemented that impact the development of local economies and adjustments of industrial structures (Xueqing and Yong, 2021; Zhang, 2021). The environmental governance process also reflects local governments’ tendency to free ride (Cai et al., 2016), the transfer of pollution shelters by enterprises (Becker and Henderson, 2000), and a reduction in the quality of green innovation (Feng et al., 2021).

As an important external governance factor, macro environmental regulation tools will directly affect enterprise performance levels in the short term. On the one hand, environmental regulation will increase enterprise cost burdens, and strict and tough environmental policies will lead to a decline in enterprise performance. On the other hand, under the continuous action of an environmental indicator system, managers will comprehensively improve production methods by improving production processes and increasing investment in green innovation to meet the increasingly stringent requirements of environmental regulation (Cui et al., 2018). However, innovation input may still create performance pressure in the short term. Therefore, whether it is cost burden or innovation investment, it will weaken enterprise profitability in the physical field, place performance pressure on managers, and promote implementation of short-term financial investment decisions.

This study divides environmental regulation tools into negative punishment type and positive incentive type. Among these, the command-type and public-participation-type environmental regulation tools involve negative punishment, requiring enterprises to meet the government or public’s emission requirements in a short time frame, mainly through fines, public opinion pressure, and other means. These negative punishment methods expand enterprise operating and cost pressures. Motivated to protect their private benefits, managers will seek to alleviate these performance pressures through short, quick financial investments. As positive incentive methods, market-incentive-type environmental regulation tools can alleviate the cost pressures enterprises face in the process of meeting environmental protection requirements in terms of funds and curb the reduction in the industrial rate of return. When an enterprise makes a good environmental protection decision, it may also get to take advantage of tax cuts and capital rewards, which have a positive impact on enterprise performance and thus help

1 It has been argued that the incentives enterprises use for managers often end up having the effect of “whipping the fast ox,” that is, the higher the manager’s profits, the greater their requirements are. In effect, the incentives actually punish the managers that are more efficient.

alleviate managers' tendency toward short-term financial investments.

To summarize, command-type and public-participation-type environmental regulation tools reduce the industrial rate of return, which will lead managers to enhance their preference for financial investment in response to short-term pressures and improve the financial investment level of enterprises. Market-incentive-type environmental regulation tools can reduce the cost pressure of enterprises in the process of environmental governance, such as through tax cuts and incentives, and alleviate managers' short-term financial investment tendencies. Accordingly, the following hypotheses are proposed.

Hypothesis 1: There is a positive correlation between negative punishment environmental regulation tools and the financial investment levels of entity enterprises. That is, the stronger the command-type and public-participation-type environmental regulation tools, the higher the financial investment levels of entity enterprises.

Hypothesis 2: There is a negative correlation between positive incentive environmental regulation tools and the financial investment levels of entity enterprises. That is, the stronger the market-incentive-type environmental regulation tools, the lower the financial investment levels of entity enterprises.

3 Materials and methods

3.1 Research sample and data selection

As a traditional industrial country, China has paid a high price for its rapid economic development in terms of resource use and environmental impact. In recent years, China has made major changes in regards to environmental protection and carbon emissions. This context is ideal for reflecting the relationship between the effectiveness of environmental regulation policies and enterprise investment. Therefore, Chinese A-share listed companies are used to test the study's hypotheses.

This study's sample is limited to entity enterprises. The annual report data of A-share non-financial and non-real estate listed companies in China's Shanghai and Shenzhen stock markets from 2007 to 2019 are used for this study's analyses. The first reason for this choice is that long-term panel data of micro samples can contain more information and reflect actual situations accurately. Second, 2007 is chosen as the starting point because the measurement of financial assets for enterprises was changed in China's accounting standards from the cost model to the fair value model in 2007. Third, although listed company data in 2020 is relatively complete, there is a serious lack of environmental-related data. To ensure preciseness, this study sets 2019 as the end time of the

sample. Since quarterly and semi-annual reports of Chinese listed companies are not required to be externally audited to ensure data authenticity, only data disclosed in annual reports are used for the analyses.

According to the research needs, firms with special treatment, such as ST, *ST, and PT², and those with missing data are excluded from the sample. A total of 23,268 valid observations were obtained. The data required for the study were obtained from the CSMAR database and the listed companies' annual reports. To control for the impact of extreme values on the model, all continuous variables were winsorized at the 1% and 99% levels.

3.2 Model construction and variable definitions

To test H₁ and H₂ and examine the impacts of different types of environmental regulation tools on the financial investment levels of entity enterprises, the following fixed-effects regression model (Eq. 1) was constructed.

$$Fin_{i,t} = \alpha_0 + \alpha_1 GZ_{p,t} + \sum \alpha_2 X_{i,t} + \sum \alpha_3 Y_{p,t} + \varepsilon_{i,p,t} \quad (1)$$

3.2.1 Explained variable

In model (Eq. 1), $Fin_{i,t}$ is a proxy variable for the financial investment level of entity enterprises, i indicates the i th listed company, and t represents time. The difficulty measuring the financial investment level of entity enterprises lies in identifying and separating the assets invested in the financial field that are different from operational investments. Based on the Penman-Nissim analysis framework and referring to Demir (2009) and Songling et al. (2021), the financial investment levels of entity enterprises are characterized by the proportion of the sum of financial assets to total assets ($Fin_{i,t}$). The larger the value, the stronger the managers' investment preference for financial assets and the higher the financial investment level of the entity enterprise. Since 2017, the Ministry of Finance has issued or revised a series of accounting standards for enterprises to regulate and update the presentation and disclosure of financial instruments, financial assets, and other related content. In view of this, the calculation formula for $Fin_{i,t}$ is adjusted around 2017. The calculation used from 2007 to 2017 is shown in Eq. 2, while that used for 2018 and 2019 is shown in Eq. 3.

² The stock exchange uses the notation "special treatment" (ST) for listed companies with abnormal financial or other conditions to alert investors of the associated risks. A company that has experienced losses for more than 3 years is then marked as *ST. PT stands for 'particular transfer' and refers to the special transfer service for suspended stocks.

$$Fin_{i,t} = \frac{\text{Financial Assets A}}{\text{Total Assets}} \quad (2)$$

$$Fin_{i,t} = \frac{\text{Financial Assets B}}{\text{Total Assets}} \quad (3)$$

Financial Assets A includes trading financial assets, held-to-maturity investments, available-for-sale financial assets, investment real estate, other financial assets, and derivative financial assets. *Financial Assets B* includes trading financial assets, held-to-maturity investments, investment real estate, other financial assets, derivative financial assets, debt investments, other debt investments, other equity instrument investments, and other non-current financial assets.

Specifically, the accounting standards before 2017 classified financial assets into four categories: financial assets measured at fair value with changes included in current profits and losses, held-to-maturity investments, loans and receivables, and available-for-sale financial assets. Because loans and receivables are closely related to the production and operation activities of entity enterprises, they are an important part of supporting and maintaining the main business. Because it is difficult to separate financial assets, based on the conservatism principle, loans and receivables are excluded from the financial assets measurement in Eq. 2. Second, according to the revision of the accounting standards in 2017, Eq. 3 divides the available-for-sale financial assets into four categories—debt investments, other debt investments, other equity instrument investments, and other non-current financial assets—and brings them into the category of financial assets. In addition, because investment real estate, trust products, and other emerging financial assets and derivative financial assets also have financial asset attributes, which can reflect the financial investment preferences of entity enterprises, Eqs 2, 3 include investment real estate, various emerging financial assets (listed in other current assets), and derivative financial assets as financial assets.

3.2.2 Explanatory variables

In model (Eq. 1), there are three types of environmental regulation tools ($GZ_{p,t}$): command-type environmental regulation tools ($GZ-Com$), public-participation-type environmental regulation tools ($GZ-Pub$), and market-incentive-type environmental regulation tools ($GZ-Inc$). p indicates the region (matched using the place of the enterprise's registration), and t indicates time.

Among the types of environmental regulation tools, command-type environmental regulation tools draw on the methods used by Fuxin et al. (2013) and Xiaosong et al. (2020). The measurement is calculated using indicators such as industrial wastewater discharge, industrial SO_2 discharge, and industrial soot discharge. The specific calculation steps are as follows. In the first step, the data of these three pollutants are standardized. The weight of each pollutant is calculated in the second step, and the third step computes the comprehensive

index ($GZ-Com$). The index is an inverse indicator. This means that the smaller the value, the lower the regional pollution emissions, and the stricter the mandatory control measures, that is, the higher the degree of command-type environmental regulation. The data required for this index are primarily obtained from the China Statistical Yearbook, China Environmental Statistical Yearbook, and China Urban Statistical Yearbook.

Existing studies have generally used the number of environmental letters and visits in each province and city to measure the degree of public-participation-type environmental regulation (Wugan and Qingqing, 2019). However, the statistics for this indicator, which were previously found in the China Environmental Yearbook and other channels, ended in 2015. Since the National People's Congress embodies the national nature of the people's democratic dictatorship, the number of recommendations by the National People's Congress is used to measure the degree of public-participation-type environmental regulation tools ($GZ-Pub$). The smaller the value of this measure, the lower the degree of public-participation-type environmental regulation. The required data are mainly retrieved from the China Environmental Yearbook.

Common measures of market-incentive-type environmental regulation tools include emission fees, tradable emission permits, and environmental taxes (Ramanathan et al., 2017; Qin et al., 2018). Referring to Hong (2008), the ratio of investment completed in regional industrial pollution control to gross regional product is used as an indicator to measure the degree of market-incentive-type environmental regulation ($GZ-Inc$). The smaller the index value, the lower the degree of market-incentive-type environmental regulation. The data required for this measurement are primarily obtained from the China Environmental Statistics Yearbook and the China Statistical Yearbook.

3.2.3 Control variables

Relevant control variables are included in the model to avoid interference by other factors that may affect financial investments of entity enterprises. In model (Eq. 1), $X_{i,t}$ represents the micro-level control variables constructed by enterprise-year, and $Y_{p,t}$ represents the macro-level control variables constructed by region-year. Micro-level control variables ($X_{i,t}$) from three aspects are used as controls: financial status, corporate governance characteristics, and enterprise characteristics. First, Duchin (2010) and Da Luz et al. (2015) confirmed that, based on the precautionary saving and speculative motivations, higher financial leverage and a lower return on assets may reduce enterprise cash holding and industrial investment levels, thus improving the financial investment level of entity enterprises. Based on this, controls for certain financial status variables are included, including financial leverage (Lev), net profit margin to total assets (ROA), return on equity (ROE), net cash flow from operations (CFO), corporate value ($TobinQ$), and total market

TABLE 1 Variable definitions.

Variable type	Variable name	Symbol	Calculation/Description
Explained variable	Financial investment level of entity enterprises	<i>Fin</i>	Sum of financial assets/total assets
Explanatory variables	Command type environmental regulation tool	<i>GZ-Com</i>	Calculated using regional industrial wastewater discharge, industrial SO ₂ emissions, and industrial soot emissions
	Public-participation type environmental regulation tool	<i>GZ-Pub</i>	Number of NPC recommendations
	Market-incentive type environmental regulation tool	<i>GZ-Inc</i>	Ratio of investment completed in regional industrial pollution control to gross regional product
Control variables	Financial leverage	<i>Lev</i>	Total liabilities/total assets
	Net profit margin on total assets	<i>ROA</i>	Net profit/Total assets
	Return on equity	<i>ROE</i>	Net profit/shareholders' equity
	Net cash flow from operations	<i>CFO</i>	Net cash flow from operating activities/total assets
	Corporate value	<i>TobinQ</i>	Market value/total assets
	Total market value	<i>TMV</i>	ln (total market value)
	Board size	<i>Board</i>	Number of members of the board of directors
	Management shareholding	<i>Mhold</i>	The value of management shareholding is 1. Otherwise, it is 0
	Senior executives' academic background	<i>Mcoll</i>	Equals 1 if senior executive has working experience in universities or scientific research institutions. Otherwise, it is 0.
	Company's establishment period	<i>Age</i>	Sample year—year company was established +1
	Enterprise nature	<i>SOE</i>	Equals 1 if the enterprise is state-owned enterprise. Otherwise, it is 0
	Technological attributes	<i>Tech</i>	Equals 1 if the enterprise has high-tech qualifications. Otherwise, it is 0
	Type of audit opinion	<i>Opin</i>	Equals 1 if the enterprise received an unqualified audit opinion. Otherwise, it is 0
	Regional gross domestic product per capita	<i>GDP_P</i>	Index of per capita GDP of provinces
	Regional fixed asset investment	<i>FA</i>	Growth rate of fixed asset investment by province
	Regional real estate investment	<i>HI</i>	Real estate investment by province/Gross regional product
Fixed effects	Industry	<i>Industry</i>	Industry dummy variables
	Year	<i>Year</i>	Year dummy variable
	Region	<i>Province</i>	Dummy variable of the province where the enterprise is registered

value (*TMV*). Second, according to Malmendier and Tate (2015) and Songling et al. (2021), a higher level of corporate governance reduces managers' independence and irrational decision-making, such as overconfidence, and restricts their short-term financial investment behavior. Based on this, controls for corporate governance characteristics are added, including board size (*Board*), management shareholding (*Mhold*), and senior executives' academic background (*MColl*). Third, Feng et al. (2022) found that there are great differences in the financial investment levels of state-owned and non-state-owned enterprises, as well as enterprises with different technological attributes. Therefore, enterprise characteristics are controlled, including the company's establishment period (*Age*), enterprise nature (*SOE*), technological attributes (*Tech*), and type of audit opinion (*Opin*). The selection of macro-level control variables ($Y_{p,t}$) draws on Akdogu and MacKay (2008), Wang et al. (2014), and Kim and Kung (2017), adding industrial factors and macroeconomic factors that may affect enterprise investment behavior, including regional gross domestic product per capita (*GDP_P*), regional fixed asset investment (*FA*), and regional real

estate investment (*HI*). In addition, to ensure the stability and accuracy of the test results, industry, time, and region fixed effects are also controlled. See Table 1 for detailed variable definitions.

3.3 Descriptive statistical analysis

Table 2 presents the descriptive statistical results of the main variables. The average financial investment level (*Fin*) of entity enterprises is 0.049, but the median is only 0.010. This indicates that the financial investment level of some entity enterprises is relatively high and even exceeds their business investment level to become the main source of profit. The mean and standard deviation of command-type environmental regulation tools (*GZ-Com*) is 0.729 and 0.607, indicating that the sample distribution in each region and each year is relatively balanced. The average value of public-participation-type environmental regulation tools (*GZ-Pub*) is 302.755. However, there is a large gap between the minimum (16) and maximum values (861), indicating that there are great differences in the degree of public participation in

TABLE 2 Descriptive statistics for the main variables.

Variables	Mean	Minimum	Median	Maximum	Standard Deviation
<i>Fin</i>	0.049	0.000	0.010	0.454	0.087
<i>GZ-Com</i>	0.729	0.000	0.661	2.179	0.607
<i>GZ-Pub</i>	302.755	16	278	861	199.034
<i>GZ-Inc</i>	0.001	0.000	0.001	0.004	0.001
<i>Lev</i>	0.442	0.059	0.439	0.884	0.200
<i>ROA</i>	0.040	−0.179	0.037	0.195	0.054
<i>ROE</i>	0.065	−0.604	0.071	0.317	0.116
<i>CFO</i>	0.050	−0.159	0.049	0.248	0.071
<i>TobinQ</i>	1.994	0.881	1.594	8.201	1.236
<i>TMV</i>	22.501	20.591	22.391	25.388	0.971
<i>Board</i>	8.859	5	9	15	1.770
<i>Mhold</i>	0.729	0	1	1	0.444
<i>Mcoll</i>	0.903	0	1	1	0.295
<i>Age</i>	17.185	4	17	32	5.750
<i>SOE</i>	0.462	0	0	1	0.499
<i>Tech</i>	0.236	0	0	1	0.425
<i>Opin</i>	0.975	0	1	1	0.157
<i>GDP_P</i>	107.599	105.730	106.880	113.640	1.915
<i>FA</i>	19.644	10.7	18.5	39.3	7.510
<i>HI</i>	0.099	0.034	0.097	0.191	0.035

different regions. The mean value of market-incentive-type environmental regulation tools (*GZ-Inc*) is 0.001, indicating that completed investment in industrial pollution control accounts for 0.1% of local GDP. In addition, the mean values of financial leverage (*Lev*), net profit margin to total assets (*ROA*), return on equity (*ROE*), and net operating cash flow (*CFO*) of the sample enterprises are 0.442, 0.040, 0.065, and 0.050, respectively. The financial indicators indicate that the sample companies are generally in good financial condition. The average size of the board of directors (*Board*) is 8.859, the proportion of companies with management shareholdings is 72.9%, and the proportion of senior executives with working experience in universities or scientific research institutions is 90.3%. Various indicators show that the corporate governance of the sample enterprises has strong convergence. Other macro control variables appear consistent with reality.

4 Results

4.1 Benchmark regression

Table 3 reports the results of testing H_1 and H_2 regarding the direct impact of different types of environmental regulation tools on the financial investment levels of entity enterprises. In Table 3, columns (1), (3), and (5) are the regression results without the control variables, and columns (2), (4), and (6) are the regression

results after adding the control variables. The coefficients of the indicators of the command-type environmental regulation tools (*GZ-Com*) are significantly negative at the 1% level. Since this indicator is an inverse indicator, the negative sign indicates that the stricter the command-type environmental regulation, the higher the financial investment level of entity enterprises, which supports Hypothesis 1. The coefficients of the indicators of public-participation-type environmental regulation tools (*GZ-Pub*) in columns (3) and (4) are significantly positive at the 1% and 5% levels, respectively, indicating that supervision using informal systems puts operating pressure on enterprises, thereby improving their financial investment levels. Both types of negative punishment measures have a boosting effect on the financial investment levels of entity enterprises, which further supports Hypothesis 1. The coefficients of the indicators of market-incentive-type environmental regulation tools (*GZ-Inc*) in columns (5) and (6) are significantly negative at the 1% and 10% levels, respectively, indicating that positive incentive measures alleviate the short-term financial investment tendency of enterprises and reduce financial investment levels, which supports Hypothesis 2.

4.2 Robustness test

4.2.1 Endogeneity test

The two-stage least square method (2SLS) is used to further alleviate potential endogeneity problems. China's

TABLE 3 Impact of environmental regulation tools on financial investment level.

<i>Variables</i>	<i>Fin</i> (1)	<i>Fin</i> (2)	<i>Fin</i> (3)	<i>Fin</i> (4)	<i>Fin</i> (5)	<i>Fin</i> (6)
<i>GZ-Com</i>	−0.003*** (−2.847)	−0.003*** (−3.038)				
<i>GZ-Pub</i>			0.000*** (13.434)	0.000** (2.181)		
<i>GZ-Inc</i>					−7.227*** (−9.998)	−1.592* (−1.831)
<i>Lev</i>		−0.094*** (−25.018)		−0.095*** (−25.086)		−0.094*** (−25.016)
<i>ROA</i>		0.073*** (2.878)		0.070*** (2.757)		0.072*** (2.837)
<i>ROE</i>		−0.026*** (−3.046)		−0.026*** (−3.012)		−0.027*** (−3.061)
<i>CFO</i>		−0.006 (−0.750)		−0.007 (−0.887)		−0.006 (−0.771)
<i>TobinQ</i>		0.001** (1.992)		0.001** (2.172)		0.001** (2.120)
<i>TMV</i>		−0.000 (−0.101)		0.000 (0.278)		−0.000 (−0.022)
<i>Board</i>		−0.001*** (−3.910)		−0.001*** (−3.974)		−0.001*** (−3.829)
<i>Mhold</i>		0.003** (2.148)		0.002* (1.934)		0.002** (2.022)
<i>Mcoll</i>		−0.013*** (−4.404)		−0.014*** (−4.488)		−0.013*** (−4.426)
<i>Age</i>		0.001*** (8.737)		0.001*** (8.984)		0.001*** (8.822)
<i>SOE</i>		0.000 (0.338)		0.001 (1.057)		0.001 (0.775)
<i>Tech</i>		−0.005*** (−3.814)		−0.005*** (−3.863)		−0.005*** (−3.864)
<i>Opin</i>		−0.008** (−2.142)		−0.008** (−2.120)		−0.008** (−2.110)
<i>GDP_P</i>		−0.004*** (−7.357)		−0.004*** (−7.118)		−0.004*** (−6.747)
<i>FA</i>		−0.000*** (−4.917)		−0.000*** (−4.094)		−0.000*** (−4.294)
<i>HI</i>		−0.015 (−0.986)		0.014 (0.998)		−0.005 (−0.301)
<i>Constant</i>	0.051*** (56.694)	0.568*** (8.496)	0.036*** (34.991)	0.541*** (8.051)	0.056*** (61.001)	0.536*** (7.884)
<i>Fixed Effects</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Obs</i>	23,268	23,268	23,268	23,268	23,268	23,268
<i>adj. R²</i>	0.000	0.164	0.009	0.164	0.003	0.164

Notes: *t*-test values in brackets, ***, **, and * indicate $p < 0.01$, $p < 0.05$, and $p < 0.10$. Fixed effects include industry, year, and province.

TABLE 4 Endogeneity results of two-stage least squares test.

Variables	GZ-Com	Fin
	(1)	(2)
NY	0.000*** (3.150)	
GZ-Com		−0.078* (−1.916)
Lev	0.053** (2.196)	−0.085*** (−17.820)
ROA	0.621*** (3.599)	0.093** (2.368)
ROE	−0.120* (−1.721)	−0.029** (−2.568)
CFO	0.147*** (2.584)	0.007 (0.597)
TobinQ	−0.028*** (−8.245)	−0.001 (−0.618)
TMV	−0.022*** (−4.758)	−0.002 (−1.430)
Board	0.001 (0.346)	−0.001*** (−3.336)
Mhold	0.036*** (4.186)	0.006*** (2.952)
Mcoll	−0.002 (−0.105)	−0.012*** (−3.663)
Age	−0.006*** (−8.506)	0.001* (1.808)
SOE	−0.148*** (−16.863)	−0.009 (−1.503)
Tech	−0.015* (−1.733)	−0.006*** (−3.806)
Opin	−0.031 (−1.217)	−0.010** (−2.254)
GDP_P	−0.018*** (−4.742)	−0.001 (−1.199)
FA	−0.005*** (−14.895)	−0.001*** (−3.602)
HI	−7.006*** (−79.602)	−0.528* (−1.855)
Constant	4.136*** (9.274)	0.374** (1.989)
Fixed Effects	Yes	Yes
Obs	20,997	20,997

Notes: *t*-test values in brackets, ***, **, and * indicate $p < 0.01$, $p < 0.05$, and $p < 0.10$. Fixed effects include industry, year, and province.

energy consumption structure is still dominated by primary energy products such as coal and oil, and clean energy consumption accounts for a relatively small proportion. The consumption of primary energy products is usually

accompanied by characteristics such as high consumption, high pollution, and low calorific value. Energy consumption efficiency has a strong correlation with the explanatory variable environmental regulation tools (GZ) and has no correlation with the disturbance term of the explained variable. Therefore, energy consumption efficiency (NY) is used as an instrumental variable (IV) and is measured by the ratio of energy consumption to the GDP of each province (see Table 4 for the test results). To ensure the IV estimates are not biased, the Cragg-Donald test for weak instruments is conducted. The F-statistic value is 10.905, which is greater than 10, indicating that the IV is not weak. In addition, there is only one IV, which is equal to the number of endogenous explanatory variables, so there is no overidentification problem. In the first stage, the coefficients of energy consumption efficiency (NY) and command-type environmental regulation tools (GZ-Com) are significantly positive at the 1% level, indicating that the instrumental variable has good explanatory power for environmental regulation tools. The regression results of the second stage are consistent with the main results, indicating that the research results remain robust after controlling for endogeneity.

4.2.2 Replacing the explained and explanatory variables

Although the interest receivable and dividends receivable earned by an entity enterprise from equity investment have not actually been collected, they can also be included as financial assets according to the accrual basis accounting principle. Based on Chengsi and Ning (2020), interest receivable and dividends receivable are incorporated into the financial asset category and a new financial investment level indicator (Fin_2) is formed for a robustness test. The test results are shown in columns (1), (2), and (3) of Table 5. When the explained variable is replaced by Fin_2 , the coefficients of the command-type (GZ-Com), public-participation-type (GZ-Pub) and market-incentive-type environmental regulation tools (GZ-Inc) are significant at the 1%, 5%, and 10% levels, respectively. These results are consistent with the main test results.

In addition, the dimension of the industrial wastewater, industrial SO₂, and industrial soot in the explanatory variable command type environmental regulation tools (GZ-Com) is reduced using the entropy method, and a new command-type environmental regulation tool index (GZ-Com₂) is constructed for a robustness test. The test results are shown in column (4) of Table 5. The coefficients of GZ-Com₂ and the financial investment level of entity enterprises (Fin) are significantly negative at the 1% level, and both the coefficients and their significance are greater than those in the original test. The results after replacing the explained and explanatory variables are consistent with the original test

TABLE 5 Robustness test results after replacing the explained and explanatory variables.

<i>Variables</i>	<i>Fin₂ (1)</i>	<i>Fin₂ (2)</i>	<i>Fin₂ (3)</i>	<i>Fin (4)</i>
<i>GZ-Com</i>	−0.003*** (−3.125)			
<i>GZ-Pub</i>		0.000** (2.100)		
<i>GZ-Inc</i>			−1.525* (−1.745)	
<i>GZ-Com₂</i>				−0.019*** (−5.551)
<i>Lev</i>	−0.094*** (−24.956)	−0.095*** (−25.023)	−0.094*** (−24.956)	−0.093*** (−24.288)
<i>ROA</i>	0.075*** (2.925)	0.072*** (2.803)	0.074*** (2.880)	0.090*** (3.417)
<i>ROE</i>	−0.027*** (−3.122)	−0.027*** (−3.087)	−0.028*** (−3.133)	−0.028*** (−3.128)
<i>CFO</i>	−0.007 (−0.803)	−0.008 (−0.938)	−0.007 (−0.826)	−0.002 (−0.252)
<i>TobinQ</i>	0.001** (2.104)	0.001** (2.287)	0.001** (2.237)	0.001** (2.174)
<i>TMV</i>	0.000 (0.206)	0.000 (0.577)	0.000 (0.290)	−0.001 (−1.020)
<i>Board</i>	−0.001*** (−4.012)	−0.001*** (−4.073)	−0.001*** (−3.935)	−0.001*** (−3.833)
<i>Mhold</i>	0.003** (2.175)	0.002** (1.962)	0.002** (2.048)	0.002 (1.402)
<i>Mcoll</i>	−0.013*** (−4.337)	−0.013*** (−4.418)	−0.013*** (−4.357)	−0.013*** (−4.287)
<i>Age</i>	0.001*** (8.903)	0.001*** (9.152)	0.001*** (8.996)	0.001*** (8.025)
<i>SOE</i>	0.000 (0.382)	0.001 (1.099)	0.001 (0.828)	−0.000 (−0.101)
<i>Tech</i>	−0.005*** (−3.773)	−0.005*** (−3.818)	−0.005*** (−3.818)	−0.005*** (−3.650)
<i>Opin</i>	−0.010** (−2.568)	−0.010** (−2.543)	−0.010** (−2.534)	−0.009** (−2.419)
<i>GDP_P</i>	−0.004*** (−7.420)	−0.004*** (−7.181)	−0.004*** (−6.820)	−0.009*** (−10.292)
<i>FA</i>	−0.000*** (−5.056)	−0.000*** (−4.241)	−0.000*** (−4.439)	−0.000*** (−4.161)
<i>HI</i>	−0.016 (−1.056)	0.013 (0.947)	−0.005 (−0.297)	−0.044*** (−2.701)
<i>Constant</i>	0.572*** (8.522)	0.545*** (8.079)	0.539*** (7.917)	1.100*** (11.027)
<i>Fixed Effects</i>	Yes	Yes	Yes	Yes
<i>Obs</i>	23,268	23,268	23,268	22,154
<i>adj. R²</i>	0.164	0.164	0.164	0.168

Notes: *t*-test values in brackets, ***, **, and * indicate $p < 0.01$, $p < 0.05$, and $p < 0.10$. Fixed effects include industry, year, and province.

TABLE 6 Robustness test results of reduced sample of non-manufacturing enterprises.

<i>Variables</i>	<i>Fin (1)</i>	<i>Fin (2)</i>	<i>Fin (3)</i>
<i>GZ-Com</i>	−0.004** (−2.070)		
<i>GZ-Pub</i>		0.000** (2.224)	
<i>GZ-Inc</i>			−2.231 (−1.382)
<i>Lev</i>	−0.105*** (−13.728)	−0.106*** (−13.752)	−0.105*** (−13.659)
<i>ROA</i>	0.006 (0.113)	−0.000 (−0.007)	0.005 (0.090)
<i>ROE</i>	−0.001 (−0.032)	−0.000 (−0.026)	−0.001 (−0.052)
<i>CFO</i>	−0.012 (−0.752)	−0.011 (−0.731)	−0.011 (−0.719)
<i>TobinQ</i>	0.005*** (3.729)	0.005*** (3.795)	0.005*** (3.816)
<i>TMV</i>	0.001 (1.239)	0.002 (1.539)	0.001 (1.225)
<i>Board</i>	−0.001 (−1.335)	−0.001 (−1.504)	−0.001 (−1.383)
<i>Mhold</i>	−0.002 (−0.890)	−0.002 (−1.075)	−0.002 (−0.960)
<i>Mcoll</i>	−0.004 (−0.778)	−0.005 (−1.016)	−0.004 (−0.873)
<i>Age</i>	0.002*** (9.229)	0.002*** (9.478)	0.002*** (9.262)
<i>SOE</i>	0.004* (1.657)	0.005** (2.045)	0.005* (1.935)
<i>Tech</i>	−0.011*** (−3.650)	−0.011*** (−3.673)	−0.011*** (−3.632)
<i>Opin</i>	−0.012 (−1.519)	−0.011 (−1.423)	−0.012 (−1.434)
<i>GDP_P</i>	−0.002** (−2.274)	−0.002** (−2.102)	−0.002* (−1.884)
<i>FA</i>	−0.001*** (−5.841)	−0.001*** (−5.548)	−0.001*** (−5.394)
<i>HI</i>	−0.049* (−1.850)	0.001 (0.030)	−0.036 (−1.359)
<i>Constant</i>	0.325*** (2.754)	0.287** (2.418)	0.285** (2.352)
<i>Fixed Effects</i>	Yes	Yes	Yes
<i>Obs</i>	7,763	7,763	7,763
<i>adj. R²</i>	0.175	0.175	0.175

Notes: *t*-test values in brackets, ***, **, and * indicate $p < 0.01$, $p < 0.05$, and $p < 0.10$. Fixed effects include industry, year, and province.

results, indicating that the research conclusions are sufficiently robust.

4.2.3 Reduced sample size

Compared with manufacturing enterprises, non-manufacturing enterprises receive relatively less attention and less intense environmental regulation. To test and verify the robustness of the main conclusion, this study draws on Qunhui's (2017) hierarchical framework and narrows the definition of entity enterprises to non-manufacturing enterprises. According to the "Guidelines for Industry Classification of Listed Companies" (revised in 2012) issued by the China Securities Regulatory Commission (CSRC), the first digit of the manufacturing industry classification is used as the standard. The sample size is reduced to 7,763 observations, and the robustness test results are shown in Table 6. Among the non-manufacturing enterprises, the same influence path as the main test remains valid in command-type (GZ-Com) and public-participation-type environmental regulation tools (GZ-Pub) at the 5% significance level. Although the test result of market-incentive-type environmental regulation tools (GZ-Inc) is negative, it is not significant. This may indicate that non-manufacturing enterprises are somewhat insensitive to environmental regulation tools.

4.3 Test of action mechanism

How managers of entity enterprises adjust their investment decisions under the influence of different types of environmental regulation tools has not previously been tested. This study's argument is that negative punishment environmental regulation tools will weaken enterprise profitability in their primary business field. The "whipping the fast ox" and "heavy rewards and light punishments" mechanisms in the managerial incentive contracts will change the preferences for and investment proportion of enterprises' physical and financial investments under environmental regulation by affecting their private benefits.

On the one hand, manager incentive compensation is usually positively correlated with enterprise short-term profits (Lin and Tomaskovic-Devey, 2013; Qiang and Bo, 2015); that is, entity enterprises will increase the compensation levels of managers who can increase enterprise performance, creating a "whipping the fast ox" effect. However, due to the inconsistent objective functions and asymmetric information between principals and agents, managers have greater discretion in making investment decisions. Under negative punitive environmental regulation tools, the increase in industrial operating costs reduces the rate of return on physical investment. To obtain rewards from "whipping the fast ox," managers will further reduce physical investment by "pulling up the flowers to make up for the house" (Tosi et al., 2000), thereby increasing the intensity of financial investment with higher short-term returns.

On the other hand, there is a theory of "heavy rewards and light punishments" in manager incentives (Junxiong, 2011). When enterprises obtain high returns through financial investment, managers will attribute this to their own efforts (Xuxian et al., 2019). However, when the income obtained from financial investment contributes little to the entity's profits, managers will blame this on external factors like market risk to avoid responsibility (Yong et al., 2017), and their own interests will suffer less damage. To summarize, command-type and public-participation-type environmental regulation tools reduce managers' private benefits through the "whipping the fast ox" and "heavy rewards and light punishments" mechanisms. To ensure stability of their private benefits in the event the entity's operating performance is impaired, managers enhance their preference for financial investment, thereby improving the financial investment level of entity enterprises.

In contrast, positive incentive environmental regulation tools mainly adjust enterprise investment decisions through marketization, which will not have a significant impact on enterprise physical operations. Moreover, when entity enterprises adopt appropriate environmental protection policies, they may also benefit from tax cuts and financial incentives to ease the cost pressure. Overall, market-incentive-type environmental regulation tools can alleviate the damage environmental regulation does to managers' private benefits through positive incentive means, weaken managers' tendency toward short-term financial investment, and reduce the financial investment level of entity enterprises. Based on this, this study proposes that different types of environmental regulation tools affect managers' private benefits and jointly affect their financial investment tendency, which in turn lead to changes in the level of financial investment of entity enterprises. This mechanism is represented by the logical chain illustrated in Figure 1.

An intermediary effect model is used to test the logical chain, where management shareholding (*Mhold*) is the intermediary variable. The test results are reported in Table 7. Columns (1), (3), and (5) present the test results when the intermediary variable is used as the dependent variable, and columns (2), (4), and (6) are the test results of the intermediary effect model. The coefficients of all key variables of the intermediary effect are significant at the 1%, 5%, and 10% levels. According to Zhonglin and Baojuan (2014), the indirect effect and the direct effect in public-participation-type environmental regulation tools have opposite signs ($|ab/c|$ is 0.022), and the effect is masked. The indirect effects in the other two types of environmental regulation tools have the same sign as the direct effects (ab/c are 0.023 and 0.000, respectively), which can be identified as a partial intermediary effect. In conclusion, the test results of the intermediary effect confirm that different types of

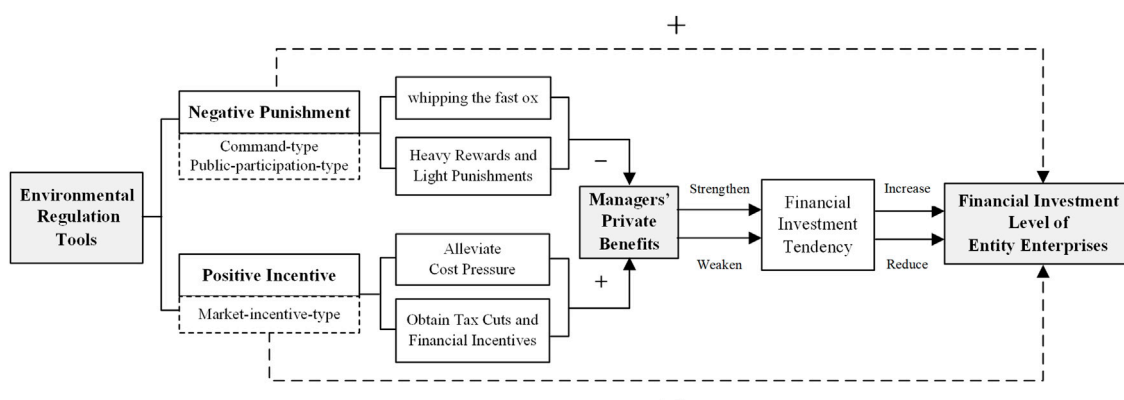


FIGURE 1

Logic chain diagram of action mechanism.

environmental regulation tools affect managers' private benefits, lead to changes in their financial investment preferences, and then affect the financial investment level of entity enterprises, verifying the existence of managerial incentives in the logical chain.

4.4 Heterogeneity test

4.4.1 Test of the moderating effect of financing constraints and relocation costs

Previous studies have found that when facing severe environmental policies, enterprises will change their R&D and investment decisions based on the degree of financing constraints and relocation costs (Chengshi and Zhenyi, 2021). On the one hand, banks will raise the interest rates on loans of polluting enterprises, creating financing constraints (Haichao et al., 2021) and enhancing the potential for enterprises to obtain short-term profits through financial investment. On the other hand, in regions with strict environmental governance policies, the "pollution paradise" hypothesis in environmental governance suggests that high-polluting enterprises will be forced to relocate to areas with lower environmental protection requirements, forming a "pollution paradise" (Kellenberg, 2009); consequently, relocation costs may affect enterprise investment decisions. This study introduces two moderating variables—the degree of financing constraints and relocation costs—to test whether they are key factors that affect the benchmark regression model. The construction of the degree of financing constraints (KZ index) draws on the methods of Kaplan and Zingales (1997) and Zhihua et al. (2014). The measurement of relocation costs (CI) refers to Chengshi and Zhenyi (2021) and is computed as the ratio of fixed assets to total assets. The results of testing the moderating effect are shown in Table 8.

The degree of financing constraints (KZ) and the multiplicative terms of the three types of environmental regulation tools are all significant at levels above 5%. Among them, the coefficient of the interaction term $GZ-Com \times KZ$ is significantly negative at the 1% level, indicating that financing constraints enhance the promotion effect of command-type environmental regulation tools on the financial investment levels of entity enterprises. This is because when entity enterprises face financing constraints, tough environmental regulation tools place great pressure on them, leading them to seek short-term profits and increasing their financial investment level. However, the moderating effect of financing constraints does not affect all negative punishment means. The coefficient of the interaction term $GZ-Pub \times KZ$ is significantly negative at the 1% level, indicating that financing constraints do not enhance the positive relationship between public-participation-type environmental regulation tools and the financial investment level of entity enterprises. There is a certain substitution effect between the two on the contribution to the growth in the financial investment level of entity enterprises. In addition, the coefficient of the interaction term $GZ-Inc \times KZ$ is significantly positive at the 5% level, indicating that financing constraints weaken the negative relationship between market-incentive-type environmental regulation tools and the financial investment level. As the degree of financing constraints increases, enterprise cash flows tend to be tight, and managers will make decisions to increase financial investment, improving the financial investment levels of entity enterprises.

The results of testing the relocation costs (CI) and various environmental regulation tools are like the financing constraint (KZ) results. Due to the existence of a "pollution paradise," enterprises tend to relocate high-pollution businesses to these locations when facing substantial pressures from environmental regulation. However, the impact of relocation costs on cash flows will become an important factor that may restrict enterprises

TABLE 7 Test of managerial incentive mechanism.

<i>Variables</i>	<i>Mhold (1)</i>	<i>Fin (2)</i>	<i>Mhold (3)</i>	<i>Fin (4)</i>	<i>Mhold (5)</i>	<i>Fin (6)</i>
<i>GZ-Com</i>	0.022*** (4.084)	−0.003*** (−3.038)				
<i>GZ-Pub</i>			0.000*** (7.735)	0.000** (2.181)		
<i>GZ-Inc</i>					−18.203*** (−3.364)	−1.592* (−1.831)
<i>Mhold</i>		0.003** (2.148)		0.002* (1.934)		0.002** (2.022)
<i>Lev</i>	−0.013 (−0.692)	−0.094*** (−25.018)	−0.013 (−0.682)	−0.095*** (−25.086)	−0.010 (−0.540)	−0.094*** (−25.016)
<i>ROA</i>	0.587*** (4.361)	0.073*** (2.878)	0.582*** (4.316)	0.070*** (2.757)	0.614*** (4.544)	0.072*** (2.837)
<i>ROE</i>	−0.134** (−2.290)	−0.026*** (−3.046)	−0.138** (−2.348)	−0.026*** (−3.012)	−0.144** (−2.436)	−0.027*** (−3.061)
<i>CFO</i>	−0.077* (−1.679)	−0.006 (−0.750)	−0.085* (−1.865)	−0.007 (−0.887)	−0.071 (−1.547)	−0.006 (−0.771)
<i>TobinQ</i>	−0.034*** (−12.225)	0.001** (1.992)	−0.034*** (−12.315)	0.001** (2.172)	−0.035*** (−12.490)	0.001** (2.120)
<i>TMV</i>	0.032*** (8.615)	−0.000 (−0.101)	0.034*** (9.226)	0.000 (0.278)	0.031*** (8.436)	−0.000 (−0.022)
<i>Board</i>	0.005*** (2.914)	−0.001*** (−3.910)	0.005*** (2.760)	−0.001*** (−3.974)	0.005*** (3.092)	−0.001*** (−3.829)
<i>Mcoll</i>	0.026* (1.790)	−0.013*** (−4.404)	0.021 (1.430)	−0.014*** (−4.488)	0.024* (1.697)	−0.013*** (−4.426)
<i>Age</i>	0.006*** (10.550)	0.001*** (8.737)	0.006*** (10.611)	0.001*** (8.984)	0.006*** (10.187)	0.001*** (8.822)
<i>SOE</i>	−0.204*** (−30.216)	0.000 (0.338)	−0.200*** (−29.401)	0.001 (1.057)	−0.206*** (−30.692)	0.001 (0.775)
<i>Tech</i>	0.038*** (5.314)	−0.005*** (−3.814)	0.036*** (5.018)	−0.005*** (−3.863)	0.036*** (5.073)	−0.005*** (−3.864)
<i>Opin</i>	0.095*** (4.587)	−0.008** (−2.142)	0.093*** (4.484)	−0.008** (−2.120)	0.094*** (4.524)	−0.008** (−2.110)
<i>GDP_P</i>	0.004 (1.314)	−0.004*** (−7.357)	0.004 (1.560)	−0.004*** (−7.118)	0.006* (1.953)	−0.004*** (−6.747)
<i>FA</i>	−0.003*** (−7.152)	−0.000*** (−4.917)	−0.002*** (−5.523)	−0.000*** (−4.094)	−0.003*** (−6.536)	−0.000*** (−4.294)
<i>HI</i>	0.142 (1.477)	−0.015 (−0.986)	0.107 (1.206)	0.014 (0.998)	−0.143 (−1.518)	−0.005 (−0.301)
<i>Constant</i>	−0.454 (−1.416)	0.568*** (8.496)	−0.590* (−1.841)	0.541*** (8.051)	−0.585* (−1.794)	0.536*** (7.884)
<i>Fixed Effects</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Obs</i>	23,268	23,268	23,268	23,268	23,268	23,268
<i>adj. R²</i>	0.103	0.164	0.104	0.164	0.102	0.164

Notes: *t*-test values in brackets, ***, **, and * indicate $p < 0.01$, $p < 0.05$, and $p < 0.10$. Fixed effects include industry, year, and province.

from making such decisions. If relocation costs are high, managers may choose short-term financial investment to alleviate the private benefits reduction caused by the pressure

of environmental protection. When relocation costs are high, the higher the pressure from environmental regulation, the higher the financial investment level of entity enterprises, similar to the

TABLE 8 Test of the moderating effect of financing constraints and relocation costs.

Variables	Fin (1)	Fin (2)	Fin (3)	Fin (4)	Fin (5)	Fin (6)
KZ	0.001** (2.212)	0.002*** (3.587)	−0.000 (−0.466)			
GZ-Com	−0.001 (−1.022)			−0.001 (−0.489)		
GZ-Com×KZ	−0.001*** (−3.204)					
GZ-Pub		0.000*** (3.712)			0.000*** (5.040)	
GZ-Pub×KZ		−0.000*** (−4.832)				
GZ-Inc			−2.757** (−2.539)			3.434** (1.971)
GZ-Inc×KZ			0.673** (2.176)			
CI				−0.099*** (−20.514)	−0.074*** (−13.288)	−0.092*** (−18.323)
GZ-Com×CI				−0.006 (−1.266)		
GZ-Pub×CI					−0.000*** (−6.307)	
GZ-Inc×CI						−10.865*** (−2.848)
Constant	0.565*** (8.441)	0.544*** (8.082)	0.539*** (7.931)	0.498*** (7.587)	0.476*** (7.207)	0.491*** (7.357)
Control Variables	Control	Control	Control	Control	Control	Control
Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Obs	23,268	23,268	23,268	23,268	23,268	23,268
adj. R ²	0.164	0.165	0.164	0.190	0.192	0.190

Notes: *t*-test values in brackets, ***, **, and * indicate $p < 0.01$, $p < 0.05$, and $p < 0.10$. Fixed effects include industry, year, and province. In the interest of saving space, the results of the control variables in Table 8 are condensed into one row.

financing constraint influence mechanism. Therefore, in the face of different environmental regulation tools, relocation costs and financing constraints play similar roles; both change managers' financial investment decisions by affecting cash flows.

4.4.2 Heterogeneity test of heavy pollution industries

The environmental protection requirements for heavy pollution industries are higher, and the performance pressure on these entity enterprises is correspondingly greater. Based on Wenjing and Xiaoyan (2015), the enterprises were grouped into heavy pollution and non-heavy pollution industry groups according to the standards in the "Guidelines for Environmental Information Disclosure of Listed Companies" published by the Ministry of Environmental Protection in 2010. Group regressions were performed, and the test results are shown in Table 9. Enterprises in 16 industries are classified as the heavy pollution industry group, including thermal power

(D44), iron and steel (C31), cement (C30), electrolytic aluminum (C32), coal (B06), metallurgy (C31/32), chemical (C26), petrochemical (C25), building materials (C30), papermaking (C22), brewing (C15), pharmaceutical (C27), fermentation and textile (C17), tanning (C19) and mining (b), and those in all other industries are included in the non-heavy pollution industry group. Columns (1), (2), and (3) are the grouping regression results of the heavy pollution industries, and columns (4), (5), and (6) are the grouping results of the non-heavy pollution industries.

From the results in columns (1) and (4), command-type environmental regulation tools (*GZ-Com*) play a significant role in both subsamples ($p < 0.05$), indicating that mandatory environmental regulation tools place great pressure on managers, leading to an increase in financial investment levels. As columns (2) and (5) show, public-participation-type environmental regulation tools (*GZ-Pub*) play a stronger role in the subsample of non-heavy pollution

TABLE 9 Grouping test results of heavy and non-heavy pollution industries.

<i>Variables</i>	<i>Fin (1)</i>	<i>Fin (2)</i>	<i>Fin (3)</i>	<i>Fin (4)</i>	<i>Fin (5)</i>	<i>Fin (6)</i>
<i>GZ-Com</i>	−0.003** (−2.269)			−0.003** (−2.250)		
<i>GZ-Pub</i>		0.000 (0.480)			0.000* (1.661)	
<i>GZ-Inc</i>			−3.157*** (−2.847)			0.903 (0.688)
<i>Lev</i>	−0.082*** (−15.080)	−0.082*** (−15.080)	−0.082*** (−15.022)	−0.101*** (−19.906)	−0.102*** (−19.976)	−0.102*** (−19.944)
<i>ROA</i>	0.089*** (2.780)	0.087*** (2.694)	0.089*** (2.758)	0.077** (2.058)	0.074** (1.972)	0.074** (1.987)
<i>ROE</i>	−0.031*** (−2.959)	−0.031*** (−2.916)	−0.032*** (−2.976)	−0.025* (−1.915)	−0.025* (−1.886)	−0.025* (−1.855)
<i>CFO</i>	−0.049*** (−3.783)	−0.051*** (−3.934)	−0.051*** (−3.898)	0.017* (1.658)	0.017 (1.605)	0.017 (1.643)
<i>TobinQ</i>	0.001 (1.405)	0.001 (1.583)	0.001 (1.503)	0.001 (1.475)	0.001 (1.572)	0.001 (1.571)
<i>TMV</i>	−0.001 (−1.493)	−0.001 (−1.348)	−0.001 (−1.459)	0.001 (1.332)	0.001 (1.606)	0.001 (1.445)
<i>Board</i>	−0.001*** (−3.348)	−0.001*** (−3.327)	−0.001*** (−3.106)	−0.001** (−2.535)	−0.001*** (−2.613)	−0.001** (−2.565)
<i>Mhold</i>	0.005*** (2.781)	0.005*** (2.711)	0.004*** (2.638)	0.001 (0.602)	0.001 (0.429)	0.001 (0.548)
<i>Mcoll</i>	−0.004 (−1.177)	−0.004 (−1.110)	−0.004 (−1.174)	−0.017*** (−4.325)	−0.017*** (−4.417)	−0.017*** (−4.332)
<i>Age</i>	0.000*** (2.663)	0.000*** (2.638)	0.000*** (2.588)	0.001*** (8.691)	0.001*** (8.997)	0.001*** (8.936)
<i>SOE</i>	−0.000 (−0.122)	0.000 (0.219)	0.000 (0.237)	0.002 (1.082)	0.003 (1.611)	0.002 (1.330)
<i>Tech</i>	0.002 (1.106)	0.002 (1.114)	0.002 (0.959)	−0.009*** (−5.554)	−0.009*** (−5.556)	−0.009*** (−5.506)
<i>Opin</i>	−0.013** (−2.313)	−0.012** (−2.271)	−0.012** (−2.294)	−0.006 (−1.234)	−0.006 (−1.225)	−0.006 (−1.207)
<i>GDP_P</i>	−0.003*** (−3.704)	−0.003*** (−3.611)	−0.003*** (−3.060)	−0.005*** (−6.445)	−0.005*** (−6.235)	−0.005*** (−6.328)
<i>FA</i>	0.000 (1.370)	0.000 (1.523)	0.000* (1.736)	−0.001*** (−6.110)	−0.000*** (−5.422)	−0.001*** (−5.908)
<i>HI</i>	−0.007 (−0.317)	0.017 (0.976)	−0.011 (−0.519)	−0.026 (−1.232)	0.006 (0.294)	0.002 (0.084)
<i>Constant</i>	0.442*** (4.729)	0.426*** (4.535)	0.390*** (4.122)	0.604*** (7.018)	0.575*** (6.653)	0.601*** (6.849)
<i>Fixed Effects</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Obs</i>	7,583	7,583	7,583	15,685	15,685	15,685
<i>adj. R²</i>	0.145	0.145	0.145	0.165	0.165	0.165

Notes: *t*-test values in brackets, ***, **, and * indicate $p < 0.01$, $p < 0.05$, and $p < 0.10$. Fixed effects include industry, year, and province.

industries ($p < 0.1$), indicating that public supervision such as public opinion does not increase pressure on managers of heavy pollution enterprises. The results in columns (3) and (6)

indicate that market-incentive-type environmental regulation tools (*GZ-Inc*) play a stronger role in the heavy pollution subsample ($p < 0.01$). Although the regression coefficient in

TABLE 10 Grouping test results of firm size.

<i>Variables</i>	<i>Fin (1)</i>	<i>Fin (2)</i>	<i>Fin (3)</i>	<i>Fin (4)</i>	<i>Fin (5)</i>	<i>Fin (6)</i>
<i>GZ-Com</i>	−0.006*** (−3.675)			−0.001 (−0.783)		
<i>GZ-Pub</i>		0.000 (0.099)			0.000*** (2.951)	
<i>GZ-Inc</i>			−1.811 (−1.339)			−1.420 (−1.306)
<i>Lev</i>	−0.087*** (−16.480)	−0.087*** (−16.588)	−0.087*** (−16.525)	−0.108*** (−18.616)	−0.108*** (−18.506)	−0.108*** (−18.589)
<i>ROA</i>	0.064* (1.789)	0.058* (1.645)	0.060* (1.675)	0.076* (1.946)	0.075* (1.920)	0.077* (1.958)
<i>ROE</i>	−0.031** (−2.295)	−0.029** (−2.178)	−0.030** (−2.217)	−0.021* (−1.822)	−0.022* (−1.891)	−0.021* (−1.872)
<i>CFO</i>	−0.004 (−0.337)	−0.005 (−0.410)	−0.004 (−0.376)	−0.010 (−0.828)	−0.011 (−0.921)	−0.010 (−0.829)
<i>TobinQ</i>	0.000 (0.405)	0.000 (0.613)	0.000 (0.578)	0.002 (1.438)	0.002 (1.397)	0.002 (1.456)
<i>TMV</i>	0.002 (1.229)	0.002 (1.347)	0.002 (1.312)	−0.004*** (−4.803)	−0.003*** (−4.290)	−0.004*** (−4.762)
<i>Board</i>	−0.001** (−2.407)	−0.001** (−2.300)	−0.001** (−2.245)	−0.001*** (−3.798)	−0.001*** (−3.937)	−0.001*** (−3.749)
<i>Mhold</i>	−0.000 (−0.145)	−0.001 (−0.323)	−0.001 (−0.346)	0.005*** (3.235)	0.005*** (3.066)	0.005*** (3.199)
<i>Mcoll</i>	−0.018*** (−4.177)	−0.018*** (−4.141)	−0.018*** (−4.172)	−0.007* (−1.835)	−0.007* (−1.931)	−0.007* (−1.859)
<i>Age</i>	0.001*** (5.570)	0.001*** (5.779)	0.001*** (5.713)	0.001*** (6.076)	0.001*** (6.273)	0.001*** (6.068)
<i>SOE</i>	0.004** (2.385)	0.005*** (2.795)	0.005*** (2.843)	−0.004** (−2.066)	−0.003 (−1.508)	−0.003* (−1.955)
<i>Tech</i>	−0.002 (−0.891)	−0.002 (−0.882)	−0.002 (−0.929)	−0.006*** (−3.355)	−0.006*** (−3.454)	−0.006*** (−3.417)
<i>Opin</i>	−0.006 (−1.186)	−0.006 (−1.131)	−0.006 (−1.143)	−0.008 (−1.446)	−0.008 (−1.432)	−0.008 (−1.437)
<i>GDP_P</i>	−0.007*** (−7.965)	−0.007*** (−7.852)	−0.006*** (−7.413)	−0.001 (−0.981)	−0.001 (−0.749)	−0.001 (−0.723)
<i>FA</i>	−0.000*** (−4.092)	−0.000*** (−3.574)	−0.000*** (−3.402)	−0.000** (−2.195)	−0.000 (−1.632)	−0.000* (−1.942)
<i>HI</i>	−0.047* (−1.775)	−0.007 (−0.274)	−0.020 (−0.743)	0.022 (1.187)	0.044*** (2.671)	0.019 (1.023)
<i>Constant</i>	0.791*** (7.798)	0.766*** (7.552)	0.745*** (7.247)	0.300*** (3.230)	0.263*** (2.802)	0.277*** (2.937)
<i>Fixed Effects</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Obs</i>	11,630	11,630	11,630	11,638	11,638	11,638
<i>adj. R²</i>	0.173	0.172	0.172	0.182	0.182	0.182

Notes: *t*-test values in brackets, ***, **, and * indicate $p < 0.01$, $p < 0.05$, and $p < 0.10$. Fixed effects include industry, year, and province.

the subsample of non-heavy pollution industries is positive, it is not significant. This shows that heavy pollution entity enterprises face strong pressure from environmental

protection indicators and urgent demand for green innovation. Positive incentive tools such as taxation can encourage them to focus more on process improvement and

green innovation, thus effectively reducing their financial investment level. However, there is not enough motivation for non-heavy pollution entity enterprises to continue to devote themselves to environmental protection innovation after they obtain environmental regulation incentives. Instead, part of the incentives may be reused for financial investment.

4.4.3 Firm size heterogeneity test

To some extent, a company's size can represent its capability to resist risk. In the presence of strict environmental regulation tools, large enterprises tend to more easily digest the performance pressure brought about by environmental protection policies and transform themselves with the help of regulatory tools. However, this is not the case for small and medium-sized enterprises. Based on Yiping et al. (2021), the study's full sample is divided into two subsamples, large enterprises and small and medium-sized enterprises (SMEs), for an additional grouping test. The median of total assets is used to divide the sample. Columns (1), (2), and (3) in Table 10 present the grouping test results of SMEs (where firm size is smaller than the median), and columns (4), (5), and (6) report the grouping test results of large enterprises (where firm size is larger than the median).

Compared with SMEs, the relationship between command-type environmental regulation tools (*GZ-Com*) and the level of financial investment (*Fin*) disappears in the subsample of large entity enterprises, but the coefficient of public-participation-type environmental regulation tools (*GZ-Pub*) is still significantly positive at the 1% level. This shows that although large enterprises can better absorb the pressure of a performance decline brought about by environmental protection policies, public-participation-type environmental regulation tools may still put more pressure on managers through corporate social responsibility, word of mouth, and other means, resulting in further improvement in the financial investment level of entity enterprises.

5 Discussion

This study uses Chinese A-share entity listed companies from 2007 to 2019 as its sample to test the relationship between various environmental regulation tools and entity enterprise financial investments. Three approaches are used to perform the tests: a fixed-effects panel regression model, the two-stage least squares method, and an intermediary effects model.

First, negative punishment-type environmental regulation tools increase the financial investment levels of entity enterprises, while positive incentive-type environmental regulation tools have a negative impact on financial investment levels (see Table 3). This indicates that command-type and public-participation-type environmental regulation tools apply "pressure mechanisms" to enterprises (He et al.,

2022), a result that is consistent with Zhang and Cheng's (2022) conclusions. This occurs because environmental regulation increases enterprise cash holding levels, which has the same effect as increasing financial investment levels; both are aimed at overcoming short-term difficulties. However, market-incentive-type environmental regulation tools do not increase enterprise financial investment levels (Xing and Fengzhong, 2022), although they do increase industrial investment such as green innovation; this applies a "compensation mechanism" (Pickman, 1998; Chen et al., 2022; Shi and Li, 2022). These findings explain why there are two opposing conclusions in the previous studies.

Second, the managerial incentive mechanism is the intermediary between environmental regulation and enterprise investment (see Table 7 and Figure 1), a finding unique to this study. Research on the relationship between macro-environmental policies and micro-enterprise decision-making primarily focuses on internal and external factors such as government subsidies (Zhang and Cheng, 2022) and financing constraints (He et al., 2022). However, enterprise investment decisions reflect the behaviors of managers who form investment preferences after combining various factors and private benefits. Different environmental regulation tools change managers' private benefits through the mechanisms of "whipping the fast ox" and "heavy rewards and light punishments," causing their investment preferences to shift to financial investment or green innovation; this in turn determines the level of investment. This is a major finding of this study.

Third, financing constraints increase the financial investment level of entity enterprises (see Table 8). The results of this study are supported by Zhang and Cheng (2022), who indicate that limited bank loans will lead to an increase in the cash holdings of high pollution enterprises due to financing constraints. Therefore, enterprises are more inclined to seek short-term profits through the financial market to alleviate the pressure brought about by tough environmental regulation tools. At the same time, relocation costs enhance the positive effect of "negative punishment" type environmental regulation tools on financial investment (see Table 8). This supports the "pollution paradise" hypothesis; that is, high-polluting enterprises will be forced to relocate to areas with lower environmental protection requirements (Jaffe et al., 1995; Kellenberg, 2009). Affected by relocation costs when faced with intense environmental regulation, entity enterprises will face serious operating pressure, and managers tend to alleviate the reduction of private benefits through short-term financial investment.

Fourth, in heavy pollution industries, the significance between "negative punishment" environmental regulation tools and financial investment levels decreases (see Table 9). Consequently, when faced with strong environmental protection indicators, heavy pollution entity enterprises tend to change the situation through process improvement and green innovation

(Guangsheng et al., 2021; Xing and Fengzhong, 2022). Moreover, large enterprises are more tolerant of command-type environmental regulation tools and more sensitive to public-participation-type environmental regulation tools (see Table 10). The larger the firm, the more likely that public-participation-type environmental regulation tools will pressure managers through social responsibility, goodwill, and other ways, increasing financial investment levels.

Overall, this study has made innovative breakthroughs in the aspects of environmental regulation, enterprise investment, managerial incentive mechanisms, and the applicability of environmental regulation tools. On the one hand, it enriches the existing literature on the transmission path of macro-environmental policies to micro-enterprise decision-making and highlights managers' behavior as the main path. On the other hand, the study proposes that there is certain applicability and combinations of environmental regulation tools, and some important combinations are revealed. When the degree of financing constraints, relocation costs, pollution, and firm size differ, the effectiveness of various types of environmental regulation tools also differs. These findings are similar to those of the latest studies by Cheng and Kong (2022), Shi and Li (2022), and Zhang et al. (2022), all of whom conclude that different environmental tools need to be used together. Therefore, as policy makers and executors, government officials and managers should fully consider multiple factors such as region, environment, and enterprise characteristics, to implement reasonable environmental regulation tools.

6 Conclusion

This study empirically tests the relationship between different types of environmental regulation tools and financial investment levels of entity enterprises using provincial data including pollution emission, pollution control investment, and recommendations by the National People's Congress, combined with data from Chinese A-share listed companies. Fixed-effects regression results show that negative punishment-type environmental regulation tools have a positive impact on the financial investment levels of entity enterprises, while positive incentive-type environmental regulation tools inhibit financial investment levels. The results of the mechanism analysis show that these impacts are formed through managerial incentive mechanisms. Heterogeneity tests found that the degree of financing constraints and relocation costs affect managers' financial investment decisions by changing enterprise cash flows, strengthening the positive effect of command-type and public-participation-type environmental regulation tools on the financial investment level, and inhibiting the negative effect of market-incentive-type environmental regulation

tools. Meanwhile, entity enterprises in high-pollution industries are more sensitive to command-type environmental regulation tools, and public-participation-type environmental regulation tools play a more significant role in large entities.

6.1 Theoretical contribution

First, although Dong et al. (2022), Chen et al. (2020), and Langpap and Shimshack (2010) all confirmed that environmental regulation tools have certain governance effects, there was still an absence of heterogeneity analysis of different types of environmental regulation tools. This resulted in two opposite conclusions about the most effective regulatory mechanism; some supported the use of "pressure mechanisms" (Mani and Wheeler, 1998; Silvia et al., 2017; Zhang et al., 2018; Petroni et al., 2019; Zhou et al., 2020), while other favored "compensation mechanisms" (Qiaoxin, 2021). This study considers two general types of environmental regulation tools—negative punishment types and positive incentive types—and examines their influence mechanisms. The results show that command-type and public-participation-type environmental regulation tools have the characteristics of negative punishment, which can positively promote the financial investment levels of entity enterprises in the short term. Market-incentive-type environmental regulation tools have the characteristics of positive incentives, which can restrain enterprise financial investment and allow enterprises to invest more resources in physical investment fields such as green transformation and development. The findings provide support for applying different types of environmental regulation tools.

Second, previous studies have focused on the impact of environmental regulation on the investment direction of enterprises (Haijing et al., 2021; Maomao and Yanyan, 2021), ignoring the influence logic between them. Few studies have deeply explored the transmission mechanism between cross-latitude factors. The results of the mechanism analysis show that environmental regulation tools mainly affect managers' private benefits through incentive mechanisms such as "whipping the fast ox" and "heavy rewards and light punishments," alleviating cost pressures, obtaining tax reductions, and financial incentives, which in turn affect their financial investment preferences, and ultimately change the financial investment levels of entity enterprises. This study decodes the "black box" between macro-environmental policy and micro-enterprise decision-making and proposes that a managerial incentive mechanism plays an intermediary role between environmental regulation tools and the financial investment levels of entity enterprises. This finding establishes the relationship between the two and reveals the specific path of policy effects.

6.2 Managerial implication

Green mountains, clear water, clear seas, and blue sky are precious treasures that cannot be bought or borrowed. Different types of environmental regulation tools have played a huge role in improving China's environmental problems. However, in the implementation process, there is a contradiction between the government's environmental competition and the environmental pressures placed on enterprises (Raffin, 2014; Dao and Edenhofer, 2018). Under the comprehensive effect of environmental regulation tools and green transformation and development, managers' investment decisions and the financial investment levels of entity enterprises will change accordingly.

This study's findings can be of significant help to enterprises in better designing their managerial incentive mechanisms and adjusting their investment direction. The study suggests that enterprises should pay attention to the long-term aspect when designing managerial incentive systems. Managers are at the helm of an enterprise. When environmental problems are more prominent, environmental protection indicators should be added to managerial incentive mechanisms, so they can actively cooperate with regional environmental protection policies to achieve green production. This finding's managerial implications confirm that the choice of environmental regulation tools, the intensity of managerial incentives, and the financial investment levels of entity enterprises need to be controlled within reasonable ranges.

6.3 Practical/social implications

First, this study provides practical suggestions for local governments as they choose environmental protection policies. During the tenure of local government officials, environmental constraints have been incorporated into the promotion competition system, forcing officials to choose between short-term and conflicting goals. The methods must suit the situation based on the pollution levels and enterprise characteristics. The findings provide a theoretical basis for the proposed policy recommendations for local governments.

Second, entity enterprises are also faced with the two contradictory goals of economic growth and short-term environmental protection. With a goal of minimizing their pains in the process of green transformation and development, this study provides decision-making ideas conducive to long-term development. For entity enterprises with low degrees of pollution, the application scenarios and practices of market-incentive-type environmental regulation tools should be expanded and strengthened. As positive incentive types of environmental regulation tools, they not only can reduce enterprise resistance to environmental protection indicators, but also avoid the emergence of "pollution paradises." For large enterprises with high

pollution, environmental violations should be curbed and punished more severely, although strict environmental law enforcement and environmental indicator systems will lead to some increase in the financial investment levels of entity enterprises, the lesser evil should be chosen when the two evils intersect. For this purpose, financial investment can be used to overcome short-term difficulties.

Third, the use of Chinese A-share listed companies as a sample for the empirical research is a valuable supplement to the study of environmental regulation effects. Unlike developed countries, which prefer market-incentive-type environmental regulation tools, developing countries mainly use command-type tools, such as performance assessments, laws, and regulation. This study overcomes the limitations of previous studies of mature companies in developed countries and provides a useful supplement and empirical reference for forming environmental regulation policies in emerging economies.

6.4 Limitations and future work

This study focuses only on the implementation effects of three types of environmental regulation tools at the micro level and thus has certain limitations. For example, although it examines the impact of environmental regulation tools on short-term financial investments of entity enterprises, its ultimate impact on green transformation and development of enterprises has not been comprehensively evaluated from a long-term perspective. At the same time, due to changes in external environments such as COVID-19 and financial supervision, current theoretical development is far behind the progress of practical evolution, which needs further in-depth research. In addition, this study only uses data from Chinese listed companies, which certainly affects generalizability. In the future, data from major developing countries such as Russia and Brazil, as well as data from developed countries like the United States, should be used for comparative analysis.

Data availability statement

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

Author contributions

DN led the conception and design of the study and wrote the original manuscript. DN and ZW collected and analyzed the data regarding environmental regulation tools and financial investment levels of entity enterprises. SY was

responsible for reviewing and editing the manuscript. All authors actively participated in the experimental design, data interpretation, and manuscript preparation, and approved the manuscript for publication.

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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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Does environmental regulation promote green merger and acquisition? Evidence from the implementation of China's newly revised *Environmental Protection Law*

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Green merger and acquisition (Green M&A) is one of the ways of corporate environmental investment, which is vital for their green transformation and sustainable development. With the implementation of the newly revised *Environmental Protection Law* in 2015, this paper investigates the impact of environmental regulation on corporate green M&A using the Difference-in-Difference method with a sample of Chinese listed companies from 2007 to 2020. We found that firms' green M&A increases significantly after the implementation of the new Environmental Protection Law. The promotion effect is more pronounced when the firm is state-owned or faces lower financing constraints. Further analysis reveals that green M&A significantly reduces firms' environmental management costs, enhances green innovation, and has no effect on market performance. This result confirms that after the implementation of the new *Environmental Protection Law*, companies engage in green M&A for cost and innovation motives rather than market motives.

KEYWORDS

environmental regulation, green merger and acquisition (GMA), environmental management costs, green innovation, market performance

1 Introduction

The rapid development of urbanization and industrialization in China has led to the overexploitation of natural resources and severe pollution of the ecological environment. Environmental protection has become a vital issue limiting economic development (Zhu et al., 2019). As the central part of the low-carbon development economic system, enterprises are the micro-units of environmental governance. However, due to the externality of environmental protection, the private costs generated by the environmental behavior of enterprises are often greater than the private benefits, resulting in the low willingness of enterprises to participate in environmental

behavior. Therefore, it is particularly important to impose external constraints and incentives to promote corporate environmental governance (Costantini and Crespi, 2008; Bi et al., 2014).

In 1989, China enacted its first *Environmental Protection Law (EPL)*. The law was comprehensively revised in 2014 and formally implemented in 2015. Compared to the old law, the new *EPL* is more stringent and flexible. It takes more severe penalties, and when it comes to projects that are not regulated by the state, the law allows different regions to consider their own natural environmental conditions, develop local environmental quality standards, and take incentive measures for enterprises with outstanding results in pollution control, thus being called the toughest *EPL*. As an important object of regulation, the change in the behavior of enterprises is the key to measuring the effectiveness of environmental legislation.

The assessment of the effects of environmental regulation has long attracted extensive scholarly attention. There are multiple ways in which environmental regulation affects firm behavior, including driving firms to invest in technological innovation to reduce compliance costs (*Porter hypothesis*, Porter and van der Linde, 1995; Zhang et al., 2017; Peng et al., 2021), or inducing firms to trade-off the benefits between factor endowments and regulatory costs, ultimately resulting in different environmental governance behaviors (*Factor endowment hypothesis*, Copeland and Taylor, 2004; *Pollution heaven hypothesis*, Copeland and Taylor, 1994; Muhammad et al., 2020). In addition, many scholars have conducted studies on the impact of environmental regulation in terms of investment decisions (Leiter et al., 2011; Zhang and Wang, 2021), firm location (Wu et al., 2017; Chen et al., 2018), pollution emissions (Shapiro and Walke, 2018; Du and Li, 2020), production factor arrangements (Liu et al., 2017), and product import and export (Shi and Xu, 2018; Brandi et al., 2020).

As an important way for companies to participate in environmental governance, green M&A has received little attention. Green M&A has a significant speed advantage compared to normal environmental investments. Through green M&A, companies can quickly enter an industry, obtain green resources or energy-saving and emission reduction technologies of the target companies (Salvi et al., 2018), simultaneously conveying their determination of environmental protection and green transformation to the market. Therefore, it is reasonable for companies to choose green M&A as a way to meet policy requirements and support their long-term growth in the face of environmental regulation. For example, in order to adjust the power supply structure of traditional thermal power generation, Jidian, a Chinese listed company, has achieved new energy transformation by acquiring a number of wind and photovoltaic power enterprises in the past decade, which has improved the company's profitability and risk resistance. Another listed company, Meijin Energy, mainly

engaged in the production and operation of coke products, is involved in hydrogen fuel cell and hydrogen energy automobile industry by acquisition, gradually promoting the layout of the whole industrial chain of clean energy.

The new *EPL* has made sufficient improvements in both penalty measures and reward-punishment mechanism, providing an ideal quasi-natural experiment for us to study the relationship between environmental regulation and corporate green M&A. With the help of this exogenous event, we build a difference-in-difference model to study the impact of environmental regulation on corporate green M&A. The results show that there is a significant increase in corporate green M&A after the implementation of the new *EPL*. In further analysis, we examine the motivations of firms to implement green M&A and find that green M&A reduces environmental costs and enhances green innovation, but does not improve market performance that traditional M&A has. Therefore, we believe that to deal with the cost and green transformation pressure brought by the new *EPL*, firms are more likely to implement green M&A for cost and innovation motives.

The contributions of this paper are as follows: First, this paper studies the impact of environmental regulation on corporate environmental behavior from an M&A perspective, which enriches the literature related to corporate environmental behavior. Second, we study the impact of environmental regulation on corporate environmental investment with the help of exogenous events. Previous studies have used pollution costs or environmental expenditures (Shadbegian and Gray, 2005; Levinson and Taylor, 2008), etc., as proxy variables for environmental regulation. This paper conducts research based on the new *Environment Protection Law* as an exogenous shock that reduces the potential endogeneity problem. Third, based on the existing environmental economics and corporate M&A theories, we analyze the motivation of firms to engage in green M&A under environmental regulation and test them empirically, enriching the relevant theoretical and empirical studies and helping to understand how environmental regulation works.

2 Theoretical analysis and research hypothesis

2.1 Motivation for corporate environmental behavior

Corporate motives for green M&A are mainly divided into internal and external aspects. The internal motivation comes from the consciousness of taking social responsibility and the strategic consideration of sustainable development. Corporate citizenship theory assumes that companies are part of society

and, like individual citizens, have both the rights and responsibilities (Valor, 2005). In addition, proper management of the relationship between the natural environment and corporate development which consistent with the concept of sustainable development, making companies more resilient in risk management and sustainable operation (Freeman and McVea, 2005; Husted and Allen, 2007; Abbas, 2020).

External incentives generated by environmental regulatory interventions are the most important external motivation. In 1920, Pigou conducted a pioneering study on the problem of externalities and pointed out that the primary contributor to environmental problems lies in their external effects (Pigou, 2002). Pollution emission allow companies to make short-term gains, but the resulting damages, such as climate change and environmental pollution, which last for tens or even hundreds of years, are borne by society. Such negative externalities distort the cost-benefit equation of corporate environmental behavior and give companies particularly little incentive to participate in addressing environmental issues, thus the role of market mechanisms is limited. To address the negative externalities of corporate pollution, policy authorities often develop environmental policies to compensate for the absence of market mechanisms (Féres and Reynaud, 2012).

2.2 Environmental regulation and corporate environmental behavior

Environmental regulation is based on public power and makes firms actively or passively bear the environmental costs generated by their product behavior. On the one hand, formal environmental regulation sets the bottom line for enterprises' environmental behavior and impose penalties for violations of relevant laws and regulations, which increases the direct cost of enterprises' production and operation (Gray and Shimshack, 2011; Ryan, 2012; Blundell et al., 2020). On the other hand, as China's environmental policy system becomes more standardized and systematic, public awareness of environmental protection has increased, environmental factors are incorporated into investment decisions by investors (Edmans, 2011; Chordia et al., 2014; Matallín-Sáez et al., 2019), and environmental performance have become an important criterion for government evaluation (Heberer and Senz, 2011). In addition, the multifaceted monitoring from the public, media, and investors constitutes informal environmental regulation (Féres and Reynaud, 2012; Chen et al., 2022), which plays an implicit role in complementing formal environmental regulation by influencing key elements related to the firms' development, such as the sale of products and services, the pricing of assets, and the cost of financing.

The constraints and incentives of environmental regulation ultimately translate into different environmental behaviors of firms. Zheng et al. (2020) analyzed the factors that affect the level of corporate environmental information disclosure and concluded that strict environmental regulation plays a vital role in improving the quality of corporate environmental information disclosure. Wang et al. (2020) and Rubashkina et al. (2015) get similar conclusions, which provides a realistic basis for the *Porter hypothesis*. Shapiro and Walker (2018) found that despite a significant increase in U.S. manufacturing output, air pollution emissions from manufacturing fell by 60%. Changes in environmental regulations drove these reductions. In summary, the existing literature on the microeconomic consequences of environmental regulation is less concerned with firms' green M&A behavior, and even less research has been conducted from the perspective of the new *EPL* implementation. Additionally, the majority of studies focus on environmental regulations and directly explore their possible impacts, but there is not much research based on the motivational level.

2.3 Environmental regulation and corporate green M&A

Based on the previous introduction of the new *EPL* and the motives of corporate green M&A. This paper argues that the main reason why the new *EPL* promotes corporate green M&A is because green M&A can bring three development benefits.

First, through green M&A, enterprise can reduce their pollution costs. Under strict environmental regulations, compliance costs are subsequently increased (Suchman, 1995). Companies that fail to assume legal responsibility for pollution control will be subject to severe penalties. Green M&A can help enterprise achieve green transformation or industry chain reconstruction, which reduces pollution control costs. On the one hand, enterprises can extend the industrial chain through green M&A. For example, thermal power companies can incorporate low-sulfur coal producers into the group through green M&A, which not only obtains clean raw materials, but also reduces the dependence of business development on the upstream of the industry chain. On the other hand, green M&A can help companies transform to cleaner production. By incorporating the M&A target into the business, enterprises can make the environmental protection business a new track for enterprise development, enjoy the preferential policies of the state for environmental protection industry, seize the opportunity of green industry development and realize business diversification.

Second, green M&A has an "eye-catching effect" and can help companies gain market attention. As an important part of

the environmental policy system, the new *EPL* is significant in improving the environmental policy system. Mullainathan and Shleifer (2005) show that companies might express their interest by making M&A announcements. Green M&A can convey the company's environmental intentions, demonstrate its commitment to environmental protection and green transformation, and create a good image of actively taking social responsibility and protecting the environment. This positive signal will be effectively reflected in the market performance of the stock.

Third, green M&A can help enterprises enhance their green innovation capability. The ultimate goal of environmental regulation is to promote the green development of enterprises, and the core of green development lies in green innovation. Through green M&A, enterprises can quickly acquire the technology needed for energy saving and emission reduction through the target firms. Compared with traditional R&D investment, direct merger and acquisition of enterprises with environmental technology can save the R&D investment of the acquirer, avoid R&D risks, improve operational efficiency, and help enterprises to quickly occupy a favorable position in the process of industry transformation (Porter and Van der Linde, 1995; Li et al., 2020). In conclusion, enterprises have a motivation to pursue green M&A in light of the new *EPL*.

Hypothesis 1: The implementation of the new *EPL* promotes the enterprises green M&A.

Hypothesis 2: Under environmental regulation, companies engage in green M&A through cost, market, and innovation motives.

3 Methodology

3.1 Sample and data collection

This paper uses Chinese A-share listed companies from 2007 to 2020 as the research sample, and the following are the data sources and sample selection rules.

The M&A data were obtained from the CSMAR database, supplemented by the CNRDS and Wind databases. 1) To ensure that the empirical analysis is conducted from the perspective of listed firms as the acquirer, only M&A events in which the listed companies are "buyers" are maintained. 2) Multiple M&A transactions announced by listed companies on the same day in which the underlying assets belong to the same target enterprise are combined into one. 3) Only successful M&A sample is retained. The following steps are carried out for further screening when studying corporate M&A performance: 1) excluding M&A events where the M&A transaction amount is less than 1 million RMB; 2) retaining

only the first M&A completed by listed companies in the same year.

The financial and corporate governance data are mainly from the CSMAR database, and the green patent data are from the CNRDS database. In the empirical analysis, all data are integrated and processed: 1) remove companies in finance, insurance, and real estate industries; 2) remove ST, PT, and insolvent companies; 3) remove samples missing key variables. A total of 5516 M&A cases and 24036 firm-year observations are obtained.

In order to avoid the influence of extreme values on the empirical results, all continuous variables are winsorized at the 1% level. Stata 17.0 econometric analysis software was used to process the data.

3.2 Definition of key variables

3.2.1 Green M&A

3.2.1.1 Identification of green M&A

Drawing on the studies of Salvi et al. (2018), this paper defines green M&A as M&A by firms to acquire energy-saving and emission-reducing technologies, improve environmental protection, and transform to low-pollution and low-energy industries. First, we collected the descriptions of target companies' business scope, and roughly screened out the samples with keywords such as environmental protection, energy saving, emission reduction, sewage disposal, waste disposal, etc. in the business scope. Then, by manually collecting the M&A announcements from the Shanghai and Shenzhen Stock Exchange, we further analyzed the background and purpose of the M&A, the business scope of the acquirer company and the target company, and the impact of the M&A on the acquirer company to determine whether the M&A was green.

3.2.1.2 Green M&A variables

In this paper, we construct two variables to measure a firm's green M&A decision. The first one is the likelihood of M&A, which is measured using the dummy variable *GM_YN*. The value of *GM_YN* is equal to 1 if firms make green M&A in a given year and 0 otherwise. The second one is the number of M&As, which is measured using the variable *GM_n*. The value of *GM_n* is the number of green M&As made by the firm in a given year.

3.2.2 Control variables

Drawing on related literature, this paper controls for the following variables, including *Size* (log of total assets), *Lev* (total debt divided by total assets), *Growth* (annual growth rate of operating income), *ROA* (return on total assets), *Top1* (top shareholder ownership), *Cashflow* (net operating cash flow),

TABLE 1 Variable definitions.

Variables	Symbols	Variable explanation
Explained variables	<i>GM_YN</i>	Whether the company has made green M&A
	<i>GM_n</i>	Number of green M&A conducted by the company
Explaining variables	<i>Ifhp</i>	Equals 1 if the firm belongs to heavily polluting industries; otherwise equals 0
	<i>Post</i>	Equals 1 in or after year 2015; otherwise equals 0
Control variables	<i>ROA</i>	Net Profit/Total Assets
	<i>Lev</i>	Long-term debt/Total assets
	<i>Lsize</i>	ln (Total assets)
	<i>Cashflow</i>	Operating cash flow/Total assets
	<i>Growth</i>	annual growth rate of operating income
	<i>Top1</i>	Shareholding ratio of the first largest shareholder
	<i>Year</i>	Annual control variables
	<i>Industry</i>	Industry control variables

and year and industry fixed effects. The specific variables are defined as shown in Table 1.

3.3 Model design

This paper constructs a difference-in-difference model with a quasi-natural experiment (the implementation of the new *EPL* in 2015). Since the policy is a uniform policy across the country, it is crucial to choose the appropriate treatment and control groups. Referring to the relevant literature design, the heavily polluting industries are more affected by the new *EPL*. Therefore, using heavy polluting enterprises as the treatment group and enterprises in other industries as the control group is beneficial to analyze the policy effects.

The identification of heavily polluting enterprises is based on the List of Listed Companies' Environmental Protection Verification Industry Classification Management, Guidelines for Disclosure of Environmental Information of Listed Companies¹ and 2012 SEC Industry Classification.

The variable *Ifhp* takes the value of 1 if the enterprise is a heavy polluter, otherwise, it takes the value of 0. *Post* is a policy dummy variable. The new *EPL* has been in effect since 1 January 2015, and *Post* equals 1 if the sample observations are in 2015 and later; otherwise equals 0.

Drawing on Shi and Xu (2018), we develop the following model to examine the impact of the new *EPL* on firms' green M&A.

$$GM_{i,t} = \alpha_0 + \beta_1 Ifhp_{i,t} + \beta_2 Ifhp_{i,t} \times Post_{i,t} + \beta_3 Controls_{i,t} + \beta_4 Year + \beta_5 Industry + \epsilon \quad (1)$$

¹ Both documents were developed by the Ministry of Environmental Protection in 2008.

TABLE 2 Descriptive statistics.

Variable	Obs	Mean	SD	Min	Median	Max
<i>GM_YN</i>	5516	0.0765	0.2658	0.0000	0.0000	1.0000
<i>GM_n</i>	422	1.1280	0.4167	1.0000	1.0000	4.0000
<i>Lsize</i>	24036	22.2125	1.3942	18.3509	22.0248	26.9506
<i>Lev</i>	24036	0.4442	0.2165	0.0505	0.4363	1.0637
<i>growth</i>	24036	2.7587	290.7512	-2.7335	0.1122	4.43e+04
<i>Cashflow</i>	24036	0.0446	0.0710	-0.1879	0.0440	0.2510
<i>ROA</i>	24036	0.0386	0.0601	-0.2060	0.0372	0.3028
<i>Top1</i>	24036	34.6199	15.0145	8.5000	32.6650	75.0000

In model (1), $GM_{i,t}$ denotes the green M&A behavior of enterprises, which is represented by two indicators, $GM\_YN_{i,t}$ and $GM\_n_{i,t}$, respectively. $Ifhp_{i,t}$ indicates whether the enterprise is a heavy polluter, and $Post_{i,t}$ is a policy dummy variable. $Controls_{i,t}$ represents other control variables that affect green M&A. This paper focuses on the coefficient of the interaction term $Ifhp_{i,t} \times Post_{i,t}$, which indicates the change in green M&A behavior of treatment group firms caused by environmental laws relative to the control group.

4 Empirical results

4.1 Descriptive statistics

Table 2 reports the results of descriptive statistics for the main variables. It can be found that a total of 5,516 valid M&A events were screened during the sample period, of which 422 were green M&A, accounting for nearly 8%. The maximum number of green M&A by the same company in a year is 4. The distribution of control variables is consistent with

TABLE 3 The impact of the new *EPL* on corporate green M&A.

	(1)	(2)	(3)	(4)
	<i>GM_n</i>	<i>GM_n</i>	<i>GM_YN</i>	<i>GM_YN</i>
<i>Ifhp</i>	−0.006** (−2.33)	−0.009*** (−2.86)	−0.004* (−1.81)	−0.006** (−2.50)
<i>Post</i>	0.012*** (4.60)		0.010*** (5.17)	
<i>Ifhp*Post</i>	0.011*** (2.63)	0.013*** (2.92)	0.010*** (2.78)	0.011*** (3.06)
<i>Lnsiz</i>	−0.001 (−0.91)	−0.000 (−0.21)	−0.001 (−1.06)	−0.000 (−0.31)
<i>Lev</i>	0.016*** (2.90)	0.011** (2.00)	0.011** (2.51)	0.009* (1.78)
<i>growth</i>	−0.000*** (−5.75)	−0.000*** (−3.34)	−0.000*** (−5.85)	−0.000*** (−3.45)
<i>Cashflow</i>	−0.052*** (−3.15)	−0.049*** (−3.18)	−0.038*** (−3.16)	−0.036*** (−2.94)
<i>ROA</i>	0.067*** (4.70)	0.064*** (4.60)	0.056*** (4.53)	0.054*** (4.36)
<i>Top1</i>	0.000*** (3.17)	0.000*** (2.86)	0.000*** (2.71)	0.000** (2.43)
<i>_cons</i>	0.013 (0.80)	−0.012 (−0.65)	0.015 (1.13)	−0.006 (−0.42)
<i>Year</i>	No	Yes	No	Yes
<i>Industry</i>	No	Yes	No	Yes
<i>Observations</i>	24036	24036	24036	24036
<i>R-squared</i>	0.003	0.024	0.003	0.020

Notes: Numbers in parentheses are t statistics. ***, **, and * indicate statistical significance at 1, 5, and 10% levels, respectively.

the performance of companies in the Chinese market, and the data is relatively representative.

4.2 The impact of the new *EPL* on corporate green M&A

Table 3 shows the regression results between the implementation of the new *EPL* and the firms green M&A. The explanatory variables in columns 1) and 2) are the likelihood of green M&A. The explanatory variables in columns 3) and 4) are the number of green M&A. Columns 2) and 4) add industry and year control variables to the original regression model. The empirical results show that the coefficients

TABLE 4 Common trend test.

	(1)	(2)
	<i>GM_YN</i>	<i>GM_n</i>
<i>Ifhp</i>	−0.006 (−1.39)	−0.009* (−1.73)
<i>Ifhp*Post</i>		
<i>before3</i>	−0.003 (−0.39)	−0.001 (−0.13)
<i>before2</i>	0.003 (0.43)	0.005 (0.54)
<i>before1</i>	−0.003 (−0.36)	−0.007 (−0.70)
<i>current</i>	−0.002 (−0.20)	−0.004 (−0.45)
<i>after1</i>	0.004 (0.50)	0.006 (0.66)
<i>after2</i>	0.018** (2.48)	0.021** (2.38)
<i>after3</i>	0.009 (1.16)	0.009 (0.96)
<i>after4</i>	0.018** (2.52)	0.022** (2.47)
<i>after5</i>	0.017** (2.29)	0.017* (1.89)
<i>Lnsiz</i>	−0.000 (−0.28)	−0.000 (−0.19)
<i>Lev</i>	0.009* (1.75)	0.011* (1.88)
<i>growth</i>	−0.000 (−0.12)	−0.000 (−0.11)
<i>Cashflow</i>	−0.035*** (−2.76)	−0.049*** (−3.15)
<i>ROA</i>	0.053*** (3.32)	0.062*** (3.25)
<i>Top1</i>	0.000** (2.54)	0.000*** (3.13)
<i>_cons</i>	−0.007 (−0.39)	−0.012 (−0.59)
<i>Year</i>	No	No
<i>Industry</i>	Yes	Yes
<i>Observations</i>	24036	24036
<i>R-squared</i>	0.021	0.024

Notes: Numbers in parentheses are t statistics. ***, **, and * indicate statistical significance at 1, 5, and 10% levels, respectively.

of the interaction terms are significantly positive at the 1% level regardless of the inclusion of industry and year control variables, showing that the probability and frequency of green M&A increased after the implementation of the new *EPL*. In addition, it is worth noting that the coefficient of *Ifhp* is significantly negative, which means the main body who prefers green M&A changed from non-heavily polluting firms to heavily polluting firms (the total effect is the sum of the coefficients of the interaction term and *Ifhp*) as a result of the new *EPL*. The new *EPL* did have a significant impact on corporate Green M&A. The results of Table 3 confirm Hypothesis 1.

4.3 Robustness tests

The DID model is applied on the premise that the treatment and control groups should have the same trend before the policy. We employ the common trend test for model validation and

construct a series of dummy variables. As shown in Table 4, *Before1-Before3* are the dummy variables before policy implementation, and *After1-After5* are the dummy variables after policy implementation. The classification of the control and treatment groups remains the same. For example, *Before1* equals 1 when the year is 2014 and *Ifhp* equals 1. *Current* equals 1 when the year is 2015 and *Ifhp* equals 1. *After1* equals 1 when the year is 2016 and *Ifhp* equals 1. Table 4 shows the results of the common trend test, the coefficients of *after2-after5* are significantly positive. The coefficients of *before1-before3* and *current* are insignificant, and the sample satisfies the common trend hypothesis.

In addition, we conduct some robustness tests on the main regression. First, we screen the M&A sample to retain the sample firms for green M&A, excluding the effect of other firm-level factors on the results. The regression results, which are shown in columns 1) and 2) of Table 5, continue to support the promotion of new *EPL* for green M&A. Second, we conduct a placebo test.

TABLE 5 Robustness tests.

	(1)	(2)	(3)	(4)
	<i>GM_YN</i>	<i>GM_n</i>	<i>GM_YN</i>	<i>GM_n</i>
<i>Ifhp</i>	−0.034** (−2.39)	−0.048*** (−2.63)	0.000 (0.10)	0.001 (0.38)
<i>Ifhp*Post</i>	0.037* (1.70)	0.040 (1.56)	−0.001 (−0.23)	−0.002 (−0.40)
<i>Lsize</i>	−0.006 (−1.23)	−0.006 (−1.01)	−0.000 (−0.06)	0.000 (0.06)
<i>Lev</i>	0.036 (1.14)	0.051 (1.41)	0.006 (1.27)	0.008 (1.47)
<i>Growth</i>	0.000 (0.76)	0.000 (0.72)	−0.000*** (−2.99)	−0.000*** (−2.62)
<i>ROA</i>	0.372*** (3.70)	0.439*** (3.90)	0.052*** (4.36)	0.062*** (4.65)
<i>Top1</i>	0.001* (1.83)	0.001** (2.25)	0.000** (2.34)	0.000*** (2.65)
<i>Cashflow</i>	−0.094 (−1.03)	−0.174 (−1.48)	−0.036*** (−3.04)	−0.050*** (−3.40)
<i>_cons</i>	0.124 (1.07)	0.103 (0.75)	−0.011 (−0.75)	−0.017 (−0.98)
<i>Year</i>	Yes	Yes	Yes	Yes
<i>Industry</i>	Yes	Yes	Yes	Yes
<i>Observations</i>	3543	3543	25060	25060
<i>R-squared</i>	0.044	0.048	0.020	0.023

Notes: Numbers in parentheses are t statistics. ***, **, and * indicate statistical significance at 1, 5, and 10% levels, respectively.

TABLE 6 Heterogeneity test for property.

	(1)	(2)	(3)	(4)
	<i>GM_YN</i>	<i>GM_YN</i>	<i>GM_n</i>	<i>GM_n</i>
<i>Ifhp</i>	−0.012*** (−3.30)	−0.001 (−0.44)	−0.018*** (−3.59)	−0.001 (−0.30)
<i>Ifhp*Post</i>	0.012** (2.09)	0.010* (1.89)	0.015** (2.16)	0.008 (1.46)
<i>Lsize</i>	0.000 (0.01)	−0.001 (−0.62)	0.001 (0.49)	−0.001 (−1.30)
<i>Lev</i>	0.016* (1.92)	0.006 (1.10)	0.018* (1.77)	0.009 (1.43)
<i>growth</i>	−0.000*** (−2.81)	−0.000 (−0.30)	−0.000*** (−2.83)	−0.000 (−0.39)
<i>Cashflow</i>	−0.011 (−0.58)	−0.050*** (−3.21)	−0.033 (−1.43)	−0.058*** (−2.74)
<i>ROA</i>	0.069*** (2.93)	0.050*** (3.37)	0.093*** (3.32)	0.054*** (3.27)
<i>Top1</i>	0.000* (1.78)	0.000 (1.44)	0.000* (1.93)	0.000* (1.75)
<i>_cons</i>	−0.020 (−0.97)	0.009 (0.44)	−0.037 (−1.43)	0.022 (0.96)
<i>Year</i>	Yes	Yes	Yes	Yes
<i>Industry</i>	Yes	Yes	Yes	Yes
<i>Observations</i>	10226	13810	10226	13810
<i>R-squared</i>	0.021	0.023	0.024	0.025

Notes: Numbers in parentheses are t statistics. ***, **, and * indicate statistical significance at 1, 5, and 10% levels, respectively.

TABLE 7 Heterogeneity test for financing constraints.

	(1)	(2)	(3)	(4)
	GM_YN	GM_YN	GM_n	GM_n
<i>Ifhp</i>	−0.007 (−1.26)	0.000 (0.02)	−0.008 (−1.31)	−0.001 (−0.18)
<i>Ifhp*Post</i>	0.029*** (2.77)	0.010 (1.17)	0.033*** (2.63)	0.012 (1.22)
<i>Lsize</i>	−0.000 (−0.05)	−0.004** (−2.20)	−0.000 (−0.10)	−0.006** (−2.28)
<i>Lev</i>	−0.006 (−0.31)	0.044** (2.45)	−0.013 (−0.64)	0.063*** (2.66)
<i>growth</i>	0.015** (2.20)	−0.000 (−0.70)	0.015** (2.07)	−0.000 (−0.86)
<i>Cashflow</i>	−0.041 (−1.13)	−0.097*** (−3.29)	−0.048 (−1.19)	−0.130*** (−3.08)
<i>ROA</i>	−0.009 (−0.16)	0.119* (1.92)	−0.030 (−0.47)	0.165** (2.05)
<i>Top1</i>	0.000 (1.43)	0.000 (0.54)	0.000 (1.45)	0.000 (1.06)
<i>_cons</i>	0.002 (0.04)	0.056 (1.58)	0.008 (0.15)	0.080* (1.81)
<i>Year</i>	Yes	Yes	Yes	Yes
<i>Industry</i>	Yes	Yes	Yes	Yes
<i>Observations</i>	3918	4402	3918	4402
<i>R-squared</i>	0.019	0.057	0.022	0.053

Notes: Numbers in parentheses are t statistics. ***, **, and * indicate statistical significance at 1, 5, and 10% levels, respectively.

By randomly classifying the sample firms, we obtain new treatment and control groups based on the proportion of the heavily polluting and ordinary firms in the previous regression. After that, we rerun the regressions, and the results are shown in columns 3) and 4) of Table 5, where the coefficients of the interaction terms are no longer significant. Combined with the findings of the main regression, this result indicates that firms that are highly affected by the new EPL show significant changes in green M&A behavior after the implementation of the new EPL, confirming that the environmental regulation has a facilitating effect on green M&A.

4.4 Heterogeneity test

4.4.1 Property heterogeneity

In addition to external policy effects, green M&A may also be influenced by the nature of the business. For example, politically

connected companies are more likely to access valuable information about policy changes, making it easier to identify investment opportunities and reduce uncertainty. In addition, governments can provide direct assistance for their transactions (Brockman et al., 2013). Therefore, based on the nature of ownership, we divide the sample firms into two subsamples, state-owned and non-state-owned, and re-run the regression to test the effect of firm nature on the previous results. Table 6 shows that the interaction term exhibits higher significance and larger coefficients in the sample of state-owned enterprises, indicating that the promotion effect of the new EPL on corporate green M&A is more pronounced among state-owned firms.

4.4.2 Financing constraints

Corporate M&A requires large amounts of financial support. Companies facing financing constraints are less likely to merge (Gorbenko and Malenko, 2018). Therefore, the condition of corporate financing constraints may affect the incentive effect of the new EPL. Based on this, we divide the sample into three groups by year according to the degree of corporate financing constraints (measured by the KZ index²). Among them, group 1 has the lowest corporate financing constraints and group 3 has the highest. We select group 1 and group 3 for regression to test the impact of financing constraints. The results in Table 7 show that the coefficients of the interaction terms are all significantly positive when companies face lower financing constraints. This means that firms with lower financing constraints are more likely to leverage their financial strengths to undertake M&A activities.

5 Motivation test

According to the analysis in the theoretical section, after the implementation of the new EPL, firms have three main motives for conducting green M&A. Green M&A may reduce the environmental protection cost (cost motive), improve the market performance (market performance motive), and increase innovation capacity (innovation motive). We will test each of these three motives.

5.1 Cost motivation

Theoretical analysis suggests that companies can enter the field of cleaner production through green M&A and benefit from synergistic effects, thereby lowering the direct regulatory costs of

² Kz index = $-3.429*cf - 5.133*div - 6.090*c + 4.410*lev + 0.483*tq$, where *cf* equals net cash flow from operations/total assets, *div* equals cash dividends/total assets, *c* equals cash holdings/total assets, *lev* equals total debt/total assets and *tq* represents Tobin's Q.

TABLE 8 Cost motivation test.

	(1)	(2)	(3)
	<i>cost_sa</i>	<i>cost_sa2</i>	<i>cost_sa3</i>
<i>GM_YN</i>	0.007 (0.76)	−0.001 (−0.43)	−0.002** (−2.37)
<i>Lnsiz</i>	−0.047 (−1.30)	−0.005*** (−9.80)	−0.004*** (−6.95)
<i>Lev</i>	0.244 (1.16)	−0.002 (−0.57)	0.001 (0.14)
<i>growth</i>	−0.000 (−1.12)	−0.000*** (−5.02)	−0.000*** (−3.05)
<i>Cashflow</i>	0.238 (1.30)	0.059*** (7.86)	0.050*** (5.42)
<i>ROA</i>	−0.660 (−0.89)	−0.004 (−0.30)	−0.020 (−1.20)
<i>Top1</i>	0.000 (0.86)	−0.000 (−0.11)	−0.000 (−0.35)
<i>_cons</i>	0.944 (1.38)	0.159*** (14.47)	0.138*** (10.43)
<i>Year</i>	Yes	Yes	Yes
<i>Industry</i>	Yes	Yes	Yes
<i>Observations</i>	5040	4268	3745
<i>R-squared</i>	0.028	0.294	0.159

Notes: Numbers in parentheses are t statistics. ***, **, and * indicate statistical significance at 1, 5, and 10% levels, respectively.

environmental regulation. These will result in lower environmental costs and improved corporate financial performance.

According to the theoretical analysis, firms engage in green M&A after implementing the new *EPL* because companies can enter the field of cleaner production through green M&A and benefit from synergistic effects, thus reducing the direct regulatory costs associated with environmental regulation. Therefore, we need to test whether green M&A has a cost-reducing effect. If firms experience a significant decrease in pollution treatment costs after green M&A, then firms' cost motive may be valid, and conversely, if green M&A does not affect pollution treatment costs, it proves that firms do not engage in green M&A for cost motive.

To test whether corporate green M&A has the above effects, we develop the following model.

$$Perform_{i,t} = \alpha_0 + \beta_1 GM\_YN_{i,t} + \beta_2 Controls_{i,t} + \beta_3 Year + \beta_4 Industry + \varepsilon \quad (2)$$

TABLE 9 Descriptive statistics for M&A performance.

VarName	Obs	Mean	SD	Min	Median	Max
<i>CAR1</i>	5281	0.0248	0.0914	−0.2108	0.0092	0.2758
<i>CAR2</i>	5301	0.0306	0.1187	−0.2777	0.0102	0.3800
<i>CAR5</i>	5313	0.0355	0.1716	−0.4113	0.0100	0.6379
<i>BHAR1</i>	5500	0.1676	1.0697	−1.0430	−0.0598	8.2649
<i>BHAR2</i>	5507	0.2407	1.5414	−1.9139	−0.1018	11.2718
<i>BHAR3</i>	5510	0.2286	1.8777	−3.1677	−0.1848	12.9934

TABLE 10 Short-term M&A performance.

	(1)	(2)	(3)
	<i>CAR1</i>	<i>CAR2</i>	<i>CAR5</i>
<i>GM_YN</i>	−0.011** (−2.26)	−0.015** (−2.31)	−0.018* (−1.93)
<i>Lnsiz</i>	−0.006*** (−5.33)	−0.008*** (−5.21)	−0.008*** (−3.38)
<i>Lev</i>	0.013 (1.56)	0.016 (1.47)	0.014 (0.84)
<i>growth</i>	0.000*** (2.91)	0.000*** (4.26)	0.000*** (3.73)
<i>Cashflow</i>	−0.038* (−1.80)	−0.049* (−1.81)	−0.041 (−1.02)
<i>ROA</i>	0.032 (1.06)	0.045 (1.17)	0.059 (1.03)
<i>Top1</i>	0.000 (0.50)	0.000 (0.47)	−0.000 (−0.47)
<i>_cons</i>	0.122*** (4.54)	0.145*** (4.17)	0.120** (2.46)
<i>Year</i>	Yes	Yes	Yes
<i>Industry</i>	Yes	Yes	Yes
<i>Observations</i>	4847	4867	4876
<i>R-squared</i>	0.063	0.069	0.067

Notes: Numbers in parentheses are t statistics. ***, **, and * indicate statistical significance at 1, 5, and 10% levels, respectively.

$Perform_{i,t}$ represents the environmental cost and financial performance of the firm, measured by the firm's management costs. To capture the lagged effects of M&A, we use management costs in periods t , $t+1$, and $t+2$ as explanatory variables. $GM\_YN_{i,t}$ indicates whether a firm has conducted a green M&A, and we focus on the coefficient of β_1 . $Controls_{i,t}$ represents other control variables that have an impact, which are introduced in Table 1. In order to better demonstrate the changes brought about by green M&A, we restrict the study sample to firms engaged in M&A.

TABLE 11 Long-term M&A performance.

	(1)	(2)	(3)
	<i>BHAR1</i>	<i>BHAR2</i>	<i>BHAR3</i>
<i>GM_YN</i>	0.104 (1.51)	0.044 (0.48)	0.029 (0.26)
<i>Lsize</i>	−0.035** (−2.05)	−0.095*** (−4.34)	−0.104*** (−3.90)
<i>Lev</i>	0.290** (2.20)	0.268 (1.59)	0.221 (1.10)
<i>growth</i>	−0.000 (−0.33)	−0.000 (−0.54)	−0.000 (−0.10)
<i>Cashflow</i>	−0.038 (−0.15)	0.101 (0.30)	0.644 (1.55)
<i>ROA</i>	1.306*** (3.15)	0.950* (1.71)	0.438 (0.65)
<i>Top1</i>	0.001 (0.67)	0.003** (1.99)	0.005*** (2.85)
<i>_cons</i>	0.845** (2.36)	2.407*** (5.08)	2.625*** (4.56)
<i>Year</i>	Yes	Yes	Yes
<i>Industry</i>	Yes	Yes	Yes
<i>Observations</i>	5051	5056	5059
<i>R-squared</i>	0.054	0.074	0.059

Notes: Numbers in parentheses are t statistics. ***, **, and * indicate statistical significance at 1, 5, and 10% levels, respectively.

Table 8 shows the regression results of green M&A with firms' environmental cost. The results show that from the third year after green M&A, the environmental costs start to decrease, which means that the implementation of green M&A has obvious cost-reducing effects and can effectively exploit the green synergy effect.

5.2 Market performance motivation

The market performance of M&A is divided into short-term and long-term. According to previous studies, the short-term market performance *CAR* is measured by the cumulative abnormal return of stocks during the window period around the first announcement date of the M&A. In this paper, the calculation is based on the market model proposed by Brown and Wamer (1985), where $AR = \sum [\sum R_{i,t} - (\alpha_i + \beta_i \times R_{m,t})]$. $R_{i,t}$ and $R_{m,t}$ are the daily returns of stock i and market m at date t considering cash dividend reinvestment. Referring to Agrawal et al. (1992), the estimation period of parameters α and β in the market model is from 150 trading days before the first announcement date of the

M&A to the first 30 trading days. We calculate the cumulative abnormal return *CAR* for M&A events with three window periods of $[-1,+1]$, $[-2,+2]$, and $[-5,+5]$.

Long-term market performance *BHAR* is measured by the difference between the return on the stock of the acquirer and the return on the corresponding portfolio in a long period. Drawing on Gregory (1997), we calculate the *BHAR* for the $[0, T]$ months after the M&A of the acquirer i as $BHAR_{i,T} = \prod_{t=0}^T (1 + R_{i,t}) - \prod_{t=0}^T (1 + R_{p,t})$, where $R_{i,t}$ and $R_{p,t}$ are the monthly returns of stock i and the corresponding portfolio p , considering cash dividend reinvestment in month t . $R_{p,t}$ is calculated using a cross-group approach: first, the listed firms are sorted from smallest to largest according to their market capitalization in June of year t and then averaged into quintiles. Then, according to the listed company's book-to-market ratio of equity (earnings per share/year-end closing) at the end of year $t-1$, the above five groups of portfolios are further sorted from smallest to largest according to the book-to-market ratio of equity, and equally divided into quintiles. Finally, the average monthly return, $R_{p,t}$, is calculated for each of the 25 portfolios in a given year. We select 12 months ($RBHAR_{12}$), 24 months ($RBHAR_{24}$) and 36 months ($RBHAR_{36}$) after M&A as the window periods of long-term market performance of M&A.

We provide descriptive statistics for the above performance variables in Table 9. Overall, firms can achieve excess returns of 2.5%–3.6% on their stock price 1–5 days after the M&A announcement and 16.8%–24.1% in the 1–3 years after the M&A.

Then, we test the market performance motive. The test of market performance motivation is similar to that of cost motivation. By looking at the impact of green M&A on market performance, we can verify whether firms will engage in green M&A for market performance motivation. The regression model follows model 2) above, $Perform_{i,t}$ denotes the short and long-term market performance of M&A, and the control variables remain consistent with the previous section.

Table 10 and Table 11 demonstrate the results of the tests of market performance motive. The results in Table 10 show that there is a significant decrease in the short-term market performance of firms after green M&A. Stock price is a reflection of investors' expectations. In their view, as a complex systemic project, M&A involves risks from the selection of target in the preparation phase, the structure design in the transaction phase, and the realization of synergies between the two parties of the transaction in the integration phase. Moreover, green M&A is unique. It can be perceived by the public as either a forced transition to comply with stricter environmental regulatory policies or as an active investment in response to a new stage of development. Both passive transformation and active investment will face great uncertainty. As a result, the market is more cautious about green M&A, and it is less likely that companies will pursue

TABLE 12 Green M&A and green innovation.

	(1)	(2)	(3)	(4)	(5)	(6)
	<i>in_patent_sa</i>	<i>in_patent_sa2</i>	<i>in_patent_sa3</i>	<i>pra_patent_sa</i>	<i>pra_patent_sa2</i>	<i>pra_patent_sa3</i>
<i>GM_YN</i>	1.573* (1.72)	2.918 (1.22)	3.371 (1.23)	0.184 (0.87)	0.855** (2.01)	0.945* (1.74)
<i>Lnsiz</i>	1.006*** (4.39)	1.830*** (2.90)	1.940*** (3.06)	0.550*** (5.00)	0.830*** (4.57)	0.856*** (4.82)
<i>Lev</i>	−0.293 (−0.49)	−1.858 (−1.20)	−2.833* (−1.65)	−0.668 (−1.40)	−0.959* (−1.89)	−1.383** (−2.27)
<i>growth</i>	−0.001 (−0.48)	−0.000 (−0.33)	0.000 (0.19)	−0.000 (−0.36)	−0.000 (−0.48)	−0.000 (−0.39)
<i>Cashflow</i>	1.396 (1.40)	3.098 (1.33)	4.423 (1.60)	0.318 (0.63)	1.344* (1.74)	1.573 (1.62)
<i>ROA</i>	4.177* (1.66)	3.134 (0.69)	0.269 (0.07)	−0.099 (−0.07)	0.959 (0.55)	0.881 (0.67)
<i>Top1</i>	−0.007 (−0.80)	−0.004 (−0.20)	0.007 (0.34)	−0.005 (−0.94)	0.001 (0.12)	0.010* (1.78)
<i>_cons</i>	−21.647*** (−4.38)	−38.470*** (−2.83)	−40.798*** (−3.00)	−11.616*** (−4.97)	−17.552*** (−4.56)	−18.185*** (−4.78)
<i>Year</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Industry</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Observations</i>	4680	3766	3225	4680	3766	3225
<i>R-squared</i>	0.044	0.044	0.060	0.048	0.073	0.117

Notes: Numbers in parentheses are t statistics. ***, **, and * indicate statistical significance at 1, 5, and 10% levels, respectively.

better market performance through green M&A. Table 11 shows the regression results for long-term market performance. Although the coefficients are positive, they are not statistically significant and do not prove that long-term market performance is improved after green M&A. In summary, there is no market performance motivation for firms to implement green M&A.

5.3 Innovation motivation

Innovation is the fundamental driving force leading the development of enterprises. Under the effect of environmental regulation, enterprises are more likely to achieve green transformation through green innovation. In order to test the innovation motive, we replace $Per\ form_{i,t}$ of model 2) with the number of green patent applications of enterprises.

Table 12 shows the empirical results of the impact of Green M&A on green innovation. It can be found that when the explanatory variable is the total number of green invention patents, green M&A has a significant positive effect on green

invention patents only in the current year. When the explanatory variable is green utility model patents, green M&A has a significant positive effect on the latter 2 years. This result confirms that green M&A by firms does promote their green innovation. For utility model patents, the promotion effect of green M&A by firms will be slightly lagged, and the result supports the innovation motive of green M&A.

6 Conclusion

The new *EPL* is an essential legal that regulates the environmental protection behavior of the whole society in the process of green development in China. Using a sample of Chinese listed companies from 2007 to 2020, we empirically examine the impact of the new *EPL* on corporate green M&A. The results show that: first, the implementation of the new *EPL* significantly increases firms' probability and frequency of green M&A. Second, the promotion effect of the new *EPL* on green M&A is more significant among SOEs or firms with low financing constraints. Third, the main reason why

environmental regulations can promote green M&A is that green M&A can reduce the environmental cost, improve financial performance, enhance green innovation, help firms better cope with environmental regulations and fit the concept of green development.

The policy implications of this paper are: 1) Empirical evidence suggests that the implementation of the new *EPL* will help promote green M&A and thus enhance green innovation. It means the “Porter hypothesis” exists in China and corporate environmental investments have an “innovation compensation” effect. Therefore, we should comply with the requirements of China’s green development trend, under the premise of unified standards and the correct exercise of discretionary administrative penalties, to develop environmental protection regulations suitable for the development of the region according to local conditions. At the same time, the government should improve the law enforcement ability of environmental regulation to provide external impetus for the green transformation of enterprises and drive high-quality economic development.

- (2) Reduce the short-sighted behavior of corporate and combine environmental protection with long-term development. According to the study’s findings, it can be seen that corporate environmental protection investment cannot result in a short-term positive market performance or long-term stock price gains. However, it can reduce corporate environmental costs, which is beneficial to the company’s financial performance. As an important environmental governance entity, corporate management should understand the relationship between environmental preservation and sustainable development, organically combine corporate environmental governance with the core business, integrate both into a unified development framework, form a positive interaction between firms’ development and ecological civilization construction, and drive sustainable corporate progress with sustainable environmental development.
- (3) In addition to promulgating environmental protection regulations, the government can give enterprises environmental protection subsidies or tax incentives to reduce their direct environmental costs. Moreover, the

government should enhance the environmental protection awareness of residents, encourage the public to purchase products and services from environmental protection enterprises, give financial or reputational incentives to enterprises that contribute to the environment, and increase the implicit benefits of their environmental protection behaviors. Companies should optimize their internal governance structure, reflect flexibly on environmental policies, plan ahead for green transformation and development, and try various forms of environmental governance practices to improve overall operational efficiency.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: <https://www.gtarsc.com/>.

Author contributions

ZH and YW performed concept development, modeling analysis, and writing. JP performed writing-review and editing. All authors contributed to the article and approved the submitted version.

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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Tax equity, green innovation and corporate sustainable development

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In the context of increasing resource scarcity and environmental pollution, achieving sustainable development with environmental friendliness at its core is essential for maintaining long-term economic growth. However, the positive environmental externalities associated with sustainable development impose an additional cost burden on enterprises. Internalizing those positive environmental externalities in the form of corporate benefits through tax policies is the key to incentivizing sustainable development. Using the reform of China's tax enforcement agency and tax enforcement system as a quasi-natural experimental context, this paper investigates the impact of tax equity on sustainable development. The empirical findings show that tax equity can promote the sustainable development of enterprises, and this promotion is achieved by enhancing corporate green innovation. Furthermore, tax equity has a stronger effect on the sustainable development of enterprises in a favorable market environment because it is more conducive to the protection of intellectual property and transformation of green innovation into tangible output. The tax equities brought about by different types of tax reforms have different effects on the sustainable development of enterprises in different life cycle stages because the types of tax inequities suffered by enterprises of different ages vary.

KEYWORDS

tax equity, sustainable development, green innovation, tax enforcement system reform, tax enforcement agency reform

1 Introduction

Since the industrial revolution, rapid economic growth has led to the overexploitation of resources and excessive discharge of industrial pollution, which have had a serious negative impact on the natural environment. This negative impact in turn affects economic development and limits the sustainability of economic growth. The international community has gradually become aware of this situation and thus adopted sustainable economic development as a core strategy. When faced with environmental problems, companies will improve their resource efficiency and seek to maintain a balance between economic output and environmental conservation to gain a sustainable competitive advantage (Hart, 1995a). The existing literature has proposed that two basic elements must be satisfied to achieve sustainable development: environmental

sustainability, which mainly refers to minimizing the environmental hazards caused by operating activities (Antolin-Lopez et al., 2016) or minimizing resource consumption (Hart, 1995b; Chow & Chen, 2012), and economic growth sustainability, which refers to maintaining long-term growth in terms of profitability and operating performance (Bansal, 2005; Steurer et al., 2005; Erol et al., 2009). In other words, corporate sustainability is defined as the pursuit of sustained economic growth in the presence of ecological constraints (Shrivastava, 1995).

Although sustainable economic development is beneficial to the long-term growth of the economy as a whole, enterprises by nature maximize their individual interests and, in the absence of external constraints, are more likely to sacrifice the natural environment or waste public resources for their own benefit—that is, the so-called “tragedy of the commons” in economic theory. This contradiction between individual rationality and group irrationality is difficult to be addressed through market mechanisms. Polluting companies make a profit by transferring the costs of pollution control to the natural environment and lack the incentive to actively minimize negative environmental externalities (Jaffe et al., 2005); companies that are devoted to emissions reduction, resource recycling, and green innovation generate knowledge spillovers and positive environmental externalities but have to bear the associated costs of those efforts, which discourages them from further investing in environmentally friendly activities (Jaffe et al., 1995; Porter & Van, 1995; Rennings, 1998; Atanassov & Liu, 2014). Therefore, the environmental externalities of enterprise development must be addressed through public economic policy interventions, and taxation is one of the most effective means of regulating the externalities of enterprise behavior (Sun et al., 2008).

In recent years, governments around the world have promulgated a variety of tax policies to encourage sustainable development. Effective tax policies require not only sensible regulations, but also the guarantees provided by a transparent tax regime. Tax equity is one of the most important indicators of the fairness of a tax regime. Tax equity is related to the credibility of the tax regulations and their enforcement. When the tax regime lacks fairness, enterprises will ignore tax policies and invest resources into obtaining tax exceptions to support their profitability, which will in turn damage its credibility. To build an efficient and fair tax regime, the Chinese government has reformed the tax enforcement system and enforcement agencies, both of which have been used to reduce information asymmetries in tax enforcement. Such reforms have played an important role in creating a fair tax regime.¹

Based on this, this paper constructs a difference-in-differences (DID) model using a sample of Chinese listed companies from 2000 to 2019 and constructs a quasi-natural experiment to test the impact of reduced tax inequity on sustainable development using the reforms of the tax enforcement system (i.e., the Golden Tax III project) and the tax enforcement agency (i.e., transferring social insurance collection from a third-party agency to the taxation department). We find that the reduction in tax inequity brought about by both reforms can significantly contribute to the sustainable development of enterprises, and the results are robust regardless of whether total factor productivity, labor intensity, or capital intensity is used as a measure of enterprise sustainability. Tax equity promotes sustainable development by increasing the number of green invention patent applications, utility patent applications, invention patent grants, and utility model grants. Furthermore, tax equity has a stronger effect on the sustainable development of enterprises in a favorable market environment, mainly because a such an environment is more conducive to green innovation. Reforming the tax enforcement system is more effective in promoting the sustainable development of young enterprises through green innovation because it is more effective in reducing information asymmetries on the collection side by breaking down tax agencies' intradepartmental information barriers while inhibiting their rent-seeking behaviors. Moreover, young enterprises typically have fewer social connections and are more likely to suffer from tax inequities. Reforming tax enforcement agencies is more effective in promoting mature enterprises through green innovation because doing so relieves information asymmetries on the payment side by coordinating social insurance premiums and taxes while reducing the inequities caused by tax evasion. Since mature enterprises are generally more willing to pay social insurance premiums, they are more likely to benefit from the tax equity brought about by tax enforcement agency reform.

The main contributions of this paper are in the following four aspects. First, the externalities of sustainable development require public policy interventions, and this paper takes tax reform as a proxy for pro-sustainable development public policy. Second, there has long been an academic debate about whether green innovation can promote sustainable development. This paper offers its perspective on this discussion by analyzing Chinese listed companies. Third, in the heterogeneity test, this paper finds that the market environment and life cycle characteristics of enterprises have heterogeneous effects on sustainable development-promoting tax equity, which provides a theoretical reference for the subsequent formulation of targeted public taxation policies. Last, two DID models that validate each other are constructed in the empirical study, which can serve as a basis for future research efforts.

¹ The details of the implementation of the reforms and their impact on tax equity are described in the institutional background section of this paper.

TABLE 1 Implementation of “Golden Tax III” in Chinese provinces and municipalities.

Year	Provinces and municipalities implementing “Golden tax III”
2013	Chongqing Municipality, Shanxi Province, Shandong Province (except Qingdao)
2014	Guangdong Province, Henan Province, Inner Mongolia Autonomous Region
2015	Hebei Province, Ningxia Hui Autonomous Region, Guizhou Province, Yunnan Province, Guangxi Zhuang Autonomous Region, Qinghai Province, Hainan Province, Tibet Autonomous Region, Gansu Province, Hunan Province, Anhui Province, Xinjiang Uygur Autonomous Region, Sichuan Province, Jilin Province
2016	Liaoning Province, Jiangxi Province, Fujian Province, Beijing Municipality, Heilongjiang Province, Tianjin, Jiangsu Province, Hubei Province, Zhejiang Province, Shaanxi Province, Shanghai Municipality, Shenzhen Municipality, Qingdao Municipality

TABLE 2 Implementation of social insurance premium collection and management reform in Chinese provinces and municipalities.

Year	Provinces and municipalities implementing social insurance premium enforcement reform
1998	Yunnan Province, Chongqing Municipality, Jiangsu Province, Anhui Province, Hubei Province, Zhejiang Province, Inner Mongolia Autonomous Region
2000	Guangdong Province, Gansu Province, Shaanxi Province, Liaoning Province, Heilongjiang Province, Hainan Province
2015	Hebei Province
2008	Ningxia Hui Autonomous Region
2017	Hainan Province
2019	Shanxi Province, Shandong Province, Guangxi Zhuang Autonomous Region, Xinjiang Uygur Autonomous Region, Tibet Autonomous Region
2020	Jilin Province, Jiangxi Province, Sichuan Province, Guizhou Province, Beijing Municipality, Tianjin Municipality, Shanghai Municipality

2 Institutional background and hypothesis development

2.1 Institutional background

Information asymmetry is an important cause of tax policy failure (Sen, 1988; Mirrlees & Vicky, 1996). Specifically, there are two main reasons for tax inequity. On the one hand, there is a certain degree of freedom in tax enforcement, and tax information asymmetries allow tax collectors to engage in rent seeking, which leads to tax inequities on the collection side; on the other hand, some enterprises may evade taxes by manipulating earnings, concealing actual income, bribing officials, *etc.*, which create tax inequities on the payment side. To address these problems, the Chinese government has adopted reforms in both the tax enforcement system and the tax enforcement agencies. Both types of reforms are aimed at creating a standardized and fair tax regime by addressing the information asymmetries that exist in tax collection and administration.

2.1.1 Reform of the tax enforcement system

The acquisition and supervision of tax-related information is an important means to ensuring the standardization of tax enforcement and provides an important guarantee against which the government implements tax policies and promotes tax equity (Gordon & Li, 2009). The Golden Tax Project, which was implemented in 1994, is a representative reform of the tax enforcement system. From 1994 to 1998, the Chinese government implemented “Golden Tax I,” which was designed to focus on the construction of a VAT cross-checking system, and promoted it in more than 50 cities. However, it did not achieve the desired effect due to the frequency of information errors caused by manual entry. To address this problem, China began to formally establish “Golden Tax II” in 1998 and rolled out the system to all provinces, prefecture-level cities and counties in 2001.

The “Golden Tax I” and “Golden Tax II” projects mainly focused on the joint verification of VAT, which could not meet the tax enforcement system’s increasingly complex needs in terms of expanding information processing and supervision, so China officially launched the “Golden Tax III” project in 2013. The “Golden Tax III” project is different from the previous two phases of the project in that it covers all tax types, generally uses big data, cloud computing and other advanced technical means, and is built following the principle of “one platform, two levels of processing, three coverage, and four systems².” This project marked a leap forward in the supervision of tax-related information: the unified technical infrastructure platform enables the smooth flow of information between taxation departments and the data can be monitored and cross-checked, the exchange of information between the State Administration of Taxation and local taxation bureaus facilitates the multi-dimensional presentation of taxpayer profiles and prevents tax evasion, and the intradepartmental information exchange compresses the freedom in local tax collection and enforcement while combatting the irregularities in tax enforcement and unfair taxation caused by corruption and collusion.

“Golden Tax III” has made greater breakthroughs than “Golden Tax I” and “Golden Tax II” in terms of influencing reform and expanding the coverage of tax types. Therefore, this paper selects

² “One platform” refers to the unified technical platform, including network hardware and basic software; “two levels of processing” refers to relying on the unified technical platform to gradually realize centralized processing of data and information in the State Administration of Taxation and provincial bureaus; “three coverage” refers to covering all tax types, covering all processes, covering state and local taxation institutions at all levels and networking with relevant departments; and “four types of systems” refers to four major applications used for tax enforcement, administrative management, managing external information and decision support.

TABLE 3 Variable names and definitions.

Variable name	Variable code	Variable definition
Total factor productivity LP	TFP_LP	Total factor productivity calculated using the LP method
Total factor productivity OP	TFP_OP	Total factor productivity calculated using the OP method
Labor intensity	LAB	As higher labor intensity indicates lower sustainability, it is defined as the negative of “cash paid to and for employees/total operating income.”
Capital intensity	CAP	Capital intensity, calculated as $\ln(\text{total assets}/\text{number of employees} + 1)$
Tax enforcement system reform	ROS	Equals one if the observation is in an area-year that has implemented the Golden Tax III according to Table 1 and zero otherwise
Tax inequity before tax enforcement system reform	UNF_ROS	Equals one if the tax burden of the firm is higher than the regional average before the implementation of the Golden Tax III project and zero otherwise
Tax enforcement agency reform	ROI	Equals one if the observation is in an area-year that has implemented social insurance premium collection agency reform according to Table 2 and zero otherwise
Tax inequity before tax enforcement agency reform	UNF_ROI	Equals one if the tax burden of the firm is higher than the regional average before the reform in social insurance premium collection and zero otherwise
Firm age	LnAge	The natural logarithm of the sample firm’s age
Firm size	LnSize	The natural logarithm of firm’s total assets
Gearing ratio	LEV	The gearing ratio of the firm
Board size	LnBSZ	The natural logarithm of the number of directors on the board plus one
Proportion of independent directors	RID	The ratio of independent directors to total directors on the board
Return on assets	ROA	Return on assets of the firm
Green invention patent application	lnGIPA	The natural logarithm of the number of green invention patent applications plus one
Green utility model application	lnGUPA	The natural logarithm of the number of green utility model patent applications plus one
Green invention patent grants	lnGIA	The natural logarithm of the number of green invention patent grants plus one
Green utility model grants	lnGUA	The natural logarithm of the number of green utility model patent grants plus one
Business environment	MI_total	Total marketization score

“Golden Tax III” as the research object for tax enforcement system reform and uses its promotion as a quasi-natural experiment to carry out empirical research. The specific rollout of “Golden Tax III” in each province and city is shown in Table 1.

2.1.2 Reform of the tax enforcement agencies

Although social insurance premiums are fees, they have the characteristics of a quasi-taxation. Among more than 170 countries and regions with social insurance premiums, 132 have taxation departments acting as social insurance premium collection and administration agencies. There has long been an ample “free space” for the collection and administration of social insurance premiums in China, and the evasion of social insurance premiums was widespread. Although the “Interim Regulations on the Collection and Payment of Social Insurance Premiums” and the Social Insurance Law of the People’s Republic of China clearly stipulate the scope and norms of collection and payment, enterprises may find ways to evade social insurance premiums by changing their governance structure, compensation plans, and ownership structure as well as by looking for loopholes in the regulatory environment (Desai and Dharmapala, 2006; Chen et al., 2010; Armstrong et al., 2015; DeBacker et al., 2015).

TABLE 4 Descriptive statistics of variables.

Variable	Obs	Mean	Std. dev	Min	Max
TFP_LP	8,935	8.184	1.010	5.785	10.720
TFP_OP	8,935	8.023	1.058	5.157	10.450
LAB	8,935	−0.116	0.082	−0.557	−0.010
CAP	8,935	14.380	0.984	9.719	20.340
UNF_ROS	8,935	0.417	0.493	0.000	1.000
ROS	8,935	0.426	0.495	0.000	1.000
UNF_ROI	8,935	0.705	0.456	0.000	1.000
ROI	8,935	0.604	0.489	0.000	1.000
LnAge	8,935	2.456	0.448	0.697	3.689
LnSize	8,935	21.510	1.129	19.346	24.032
LnLEV	8,935	0.445	0.194	0.053	0.973
LnBSZ	8,935	2.079	0.720	0.179	3.296
RID	8,935	0.372	0.119	0.168	0.576
ROA	8,935	0.045	0.054	−0.121	0.243
lnGIPA	8,935	0.217	0.584	0.000	3.091
lnGUPA	8,935	0.169	0.493	0.000	2.708
lnGIA	8,935	0.135	0.311	0.000	2.484
lnGUA	8,935	0.115	0.334	0.000	1.926
MI_total	8,874	8.270	1.915	−1.420	11.710

TABLE 5 Baseline regression results.

Variables	Tax enforcement system reform	Tax enforcement agency reform
	(1)	(2)
	TFP_LP	TFP_LP
ROS	−0.076** (−2.39)	—
UNF_ROS	−0.353*** (−22.38)	—
UNF_ROS×ROS	0.130*** (5.88)	—
ROI	—	−0.080* (−1.66)
UNF_ROI	—	−0.306*** (−15.66)
UNF_ROI×ROI	—	0.279*** (5.47)
Controls	YES	YES
Constant	1.749*** (21.78)	1.744*** (21.41)
Observations	8,935	8,935
R-squared	0.769	0.759
Year FE	YES	YES
Ind FE	YES	YES

Note: ***, **, and * indicate that the estimates are significant at the 1%, 5%, and 10% levels, respectively. T-values are reported in parentheses.

As the most critical factor at the enforcement level, the operation of collection agencies has a significant impact on the standardization of tax and social insurance premium collection as well as the prevention of tax evasion. In 1998, the Ministry of Finance, the Ministry of Labor, the People's Bank of China, and the State Administration of Taxation jointly issued the "Notice on the Issuance of Interim Provisions on the Implementation of Two Lines of Management of the Basic Pension Insurance Fund for Enterprise Employees," which clearly stipulates that both social insurance agencies and taxation departments are the legal agencies for collecting and managing social insurance premiums and that localities are free to choose between the two. In 1999, the 13th executive meeting of the State Council considered and adopted the "Provisional Regulations on Collection and Payment of Social Insurance Premiums," which reconfirmed the collection and administration departments. Although both the social insurance and taxation departments are the legal collection agencies for social insurance premiums, the taxation departments are relatively more regulated and thus more aggressive in their collection efforts. On the one hand, there is a connection between social insurance premiums and income tax and thus the collection of social

insurance premiums by the taxation department can allow for more efficient supervision of tax evasion by cross-checking information; on the other hand, the taxation department has stronger enforcement capabilities, a more complete collection and control system, and takes a firmer stance against tax evasion. To restrain tax evasion, more local governments are choosing to implement tax enforcement agency reform and replace third-party agencies with taxation departments as collectors of social insurance premiums. The specific rollout is shown in Table 2.

2.2 Hypothesis development

Tax enforcement reform contributes to tax equity by reducing information asymmetries, and the impact of corporate tax equity on sustainable development can be analyzed from both the corporate and market perspectives. From the corporate side, reducing tax inequities promotes green innovation and sustainable development through three main pathways. First, reducing tax inequities means that enterprises face a less unfair tax burden, which enables them to retain more profits such that they have more resources to invest in green innovation. Second, reducing tax inequities makes enterprises more optimistic about their future prospects, boosts their confidence, and encourages them to respond more positively to environmental protection and innovation policy guidance, which in turn motivates them to invest in green innovation resources (Liu et al., 2022). Third, enterprises facing fewer tax inequities are more inclined to send positive signals to the market, which reduces their cost of financing and relieves their financing constraints (Sialm, 2006; Baum et al., 2009; Croce et al., 2012; Francis et al., 2014). From the market side, tax equity reduces the distortions in resource allocation caused by the government's "special care," thus alleviating the problem of mismatched production resources and facilitating the flow of production materials to more efficient enterprises. In light of the above analysis, the first hypothesis of this paper can be proposed:

Hypothesis 1: Tax equity promotes sustainable development.

The reduction in tax inequities brought about by tax enforcement reform will promote the sustainable development of enterprises. According to the theoretical analysis in the previous section, it can be seen that tax equity promotes green innovation. Therefore, this paper analyzes the influencing mechanism of tax equity on the sustainable development of enterprises from the perspective of green innovation.

Innovation is the core driver of enterprise development, and green innovation can improve enterprises' production processes, convert waste into goods, reduce compliance costs, and enhance enterprises' environmental reputation and competitive advantages, all of which promote sustainable development (Hart, 1995a; Porter and Van, 1995; Sharma and Vredenburg, 1998; Eiadat, 2008). First, green innovation can help firms build a

TABLE 6 The dynamic effects of tax enforcement reforms.

Variables	Tax enforcement system reform			Tax enforcement agency reform		
	Experimental group	Control group	Full sample	Experimental group	Control group	Full sample
	(1)	(2)	(3)	(4)	(5)	(6)
	TFP_LP	TFP_LP	TFP_LP	TFP_LP	TFP_LP	TFP_LP
ROS_-5/ROI_-5	0.407 (1.61)	0.055 (0.38)	0.095 (1.31)	-0.249* (-1.74)	0.297 (0.45)	-0.141 (-0.41)
ROS_-4/ROI_-4	0.342 (1.60)	0.090 (0.65)	0.109 (1.54)	-0.091 (-0.84)	0.324 (0.49)	-0.033 (-0.29)
ROS_-3/ROI_-3	0.245 (1.25)	0.117 (0.88)	0.185 (1.01)	-0.113 (-1.03)	0.719 (1.18)	0.114 (0.83)
ROS_-2/ROI_-2	0.288 (1.58)	0.123 (0.95)	0.085 (1.21)	-0.025 (-0.25)	0.351 (0.54)	-0.022 (-0.23)
ROS_-1/ROI_-1	0.260 (1.52)	0.117 (0.94)	0.166 (0.88)	-0.017 (-0.19)	0.165 (0.25)	0.023 (0.15)
ROS_0/ROI_0	0.519** (2.20)	0.136 (1.13)	0.188* (1.93)	0.240*** (3.13)	0.135 (0.18)	0.158** (1.97)
ROS_1/ROI_1	0.329** (2.08)	0.109 (0.94)	0.225** (2.03)	0.272*** (3.74)	0.158 (0.21)	0.097* (1.72)
ROS_2/ROI_2	0.264* (1.82)	0.094 (0.84)	0.194** (2.00)	0.293*** (4.51)	0.149 (0.20)	0.191 (1.21)
ROS_3/ROI_3	0.284** (2.12)	0.160 (1.45)	0.186** (1.99)	0.238*** (3.62)	0.155 (0.21)	0.179 (1.48)
ROS_4/ROI_4	0.305** (2.40)	0.130 (1.28)	0.196** (2.14)	0.199*** (3.74)	0.046 (0.06)	0.053 (0.93)
ROS_5/ROI_5	0.277** (2.34)	0.144 (1.31)	0.154* (1.76)	0.140* (1.82)	0.134 (0.18)	0.026 (0.48)
Controls	YES	YES	YES	YES	YES	YES
Constant	0.645*** (3.59)	1.676*** (11.02)	1.615*** (14.70)	1.772*** (16.61)	1.177** (2.13)	1.815*** (19.48)
Observations	3,426	5,509	8,935	3,426	5,509	8,935
R-squared	0.655	0.765	0.754	0.753	0.778	0.754
Year FE	YES	YES	YES	YES	YES	YES
Ind FE	YES	YES	YES	YES	YES	YES

Note: ***, **, and * indicate that the estimates are significant at the 1%, 5%, and 10% levels, respectively. T-values are reported in parentheses. Due to space limitations, only the dynamic regression results for the 5 years before and after the implementation of the reform are presented.

competitive advantage by reducing their costs while contributing to the development of differentiated products (Porter and Van, 1995). Second, firms that engage in green innovation can benefit from a reduced cost of compliance with government environmental regulations (Hart, 1995b). Third, green innovation can help firms improve their market position (Mirata and Emtairah, 2005; Bernauer et al., 2007; Tian et al., 2021). Fourth, green innovation can enhance firms' environmental reputation (Eiadat et al., 2008). Studies have shown that consumers are more inclined to buy products that support green innovation concepts (Heun et al., 2014; Tully &

Winer, 2014), and some consumers are inclined to pay higher prices for environmentally friendly products and services (Bhat, 1993). Fifth, the adoption of green innovation strategies optimizes operational processes and thus improves economic performance (Banerjee, 2001). Furthermore, environmental performance makes not only a direct but also an indirect contribution to economic performance (Shrivastava, 1995). Most scholars believe that corporate green innovation helps firms build sustainable competitive advantages (e.g., Porter and Van, 1995; Brunnermeier & Cohen, 2003; Johnstone, 2007). Therefore, this paper proposes its second hypothesis:

TABLE 7 Regression results for the placebo test.

Variables	Tax enforcement system reform	Tax enforcement agency reform
	(1)	(2)
	TFP_LP	TFP_LP
ROS_pb	0.132*** (5.28)	—
UNF_ROS_pb	−0.245*** (−11.19)	—
UNF_ROS_pb×ROS_pb	0.026 (0.91)	—
ROI_pb	—	0.131*** (5.34)
UNF_ROI_pb	—	−0.245*** (−11.10)
UNF_ROI_pb×ROI_pb	—	0.024 (0.83)
Controls	YES	YES
Constant	1.471*** (15.67)	1.471*** (15.69)
Observations	8,935	8,935
R-squared	0.646	0.646
Year FE	YES	YES
Ind FE	YES	YES

Note: ***, **, and * indicate that the estimates are significant at the 1%, 5%, and 10% levels, respectively. T-values are reported in parentheses.

Hypothesis 2: Green innovation is a mediating mechanism through which tax equity promotes sustainable development.

3 Research design

3.1 Sample

This paper selects Chinese listed companies from 2000 to 2019 as the sample. Financial companies, companies with owner's equity of less than zero, companies under special treatment, and companies with less than 3 years of innovation data are removed from the sample, leaving a final sample of 8,935 observations. Patent data are manually collected from the website of the State Intellectual Property Office, and all financial data are obtained from the CSMAR database. Data on tax enforcement reforms at both the prefectural and provincial levels are obtained from the State Council website and local government websites, and data on the market environment are obtained from the Marketization Index published by Fan Gang and Wang Xiaolu (Fan et al., 2001). To eliminate the effect of extreme values, all continuous variables are winsorized at the 1% and 99% percentiles.

3.2 Variables

In this paper, total factor productivity calculated using the LP method (Levinsohn and Petrin, 2003) is chosen as a measure of enterprise sustainability and total factor productivity calculated using the OP method (Olley and Pakes, 1996), capital intensity and labor intensity (Solow, 1956; Forbes, 2002; Carayannis, 2004) are used as alternative indicators.

In terms of explanatory variables, this paper uses two dummy variables to indicate whether the firm has experienced tax enforcement reform (*ROS/ROI*). A value of one is assigned if the firm is in an area-year where tax enforcement reform has been implemented and zero otherwise. *UNF_ROS/UNF_ROI* is used to indicate whether the firm suffered from tax inequity before the reform was implemented. A value of one is assigned if the tax burden of the firm is higher than the regional average before the reform and zero otherwise. The product of *ROS/ROI* and *UNF_ROS/UNF_ROI* (*ROS*UNF_ROS/ROI*UNF_ROI*) therefore represents the reduction in tax inequity, as the reforms reduce information asymmetries and thus reduce tax inequity from both the government and corporate sides (Allingham and Sandmo, 1972; Slemrod et al., 2001; Desai and Dharmapala, 2006; Kleven et al., 2011; Armstrong et al., 2015; DeBacker et al., 2015; Pomeranz, 2015; Carrillo et al., 2017; Chen, 2017).

To capture the green innovation of the sample firms, this paper uses the number of green invention patent applications, utility model patent applications, invention patent grants, and utility model patent grants. The detailed definitions of the variables are presented in Table 3.

Table 4 presents the descriptive statistics of the variables. The minimum value of *TFP_LP* is 5.785, the maximum value is 10.720, and the standard deviation is 1.010, which indicates that enterprise sustainability varies widely. The mean of *ROS* is 0.426 and the mean of *ROI* is 0.604, which indicates that roughly half of the observations have experienced tax enforcement reform. The green innovation indicators (*lnGIPA*, *lnGUPA*, *lnGIA*, *lnGIA*) vary widely among enterprises.

3.3 Model

To test the impact of reduced tax inequity on the sustainable development of enterprises, this paper selects tax enforcement reform (i.e., tax enforcement system reform represented by the Golden Tax III project and tax enforcement agency reform represented by switching social insurance premium collection to the tax departments) as quasi-natural experiments, respectively, and designs a DID model to observe the effect of the reduced tax inequity brought about by tax enforcement reform on the sustainable development of enterprises. Based on this, the paper constructs the following models:

TABLE 8 Regression results substituting alternative measures of sustainable development.

Variables	Tax enforcement system reform	Tax enforcement agency reform	Tax enforcement system reform	Tax enforcement agency reform	Tax enforcement system reform	Tax enforcement agency reform
	(1)	(2)	(3)	(4)	(5)	(6)
	TFP_OP	TFP_OP	LAB	LAB	CAP	CAP
ROS	-0.057* (-1.87)	—	0.020*** (9.11)	—	0.057 (0.65)	—
UNF_ROS	-0.325*** (-21.63)	—	0.009*** (3.88)	—	-0.132*** (-3.15)	—
UNF_ROS x ROS	0.116*** (5.49)	—	0.006* (1.94)	—	0.158*** (2.64)	—
ROI	—	-0.044 (-0.96)	—	-0.002 (-0.28)	—	0.334*** (2.72)
UNF_ROI	—	-0.281*** (-15.10)	—	-0.010*** (-3.80)	—	-0.360*** (-7.41)
UNF_ROI x ROI	—	0.226*** (4.66)	—	0.011* (1.69)	—	0.230* (1.76)
Controls	YES	YES	YES	YES	YES	YES
Constant	1.840*** (24.02)	1.841*** (23.71)	0.212*** (21.55)	-0.263*** (-24.36)	-1.009*** (-4.36)	-2.989*** (-12.71)
Observations	8,935	8,935	8,935	8,935	8,935	8,935
R-squared	0.770	0.760	0.329	0.337	0.110	0.155
Year FE	YES	YES	YES	YES	YES	YES
Ind FE	YES	YES	YES	YES	YES	YES

Note: ***, **, and * indicate that the estimates are significant at the 1%, 5%, and 10% levels, respectively. T-values are reported in parentheses.

- 1) Using the tax enforcement system reform represented by the Golden Tax III project as the quasi-natural experiment:

$$TFP_{LP_{it}} = \alpha_0 + \alpha_1 \cdot ROS_{it} + \alpha_2 \cdot UNF_{ROS_{it}} + \alpha_3 \cdot ROS_{it} \times UNF_{ROS_{it}} + \alpha_4 \cdot LnAge_{it} + \alpha_5 \cdot LnSize_{it-1} + \alpha_6 \cdot LnLEV_{it-1} + \alpha_7 \cdot LnBSZ_{it-1} + \alpha_8 \cdot RID_{it-1} + \alpha_9 \cdot ROA_{it-1} + YearFE + IndustryFE + \varepsilon_{it} \quad (1)$$

where $TFP_{LP_{it}}$ is the explanatory variable that indicates the sustainable development of firm i in year t , ROS_{it} is the indicator for tax enforcement system reform, and $UNF_{ROS_{it}}$ indicates whether the firm suffered from tax inequity before the tax enforcement system reform. $ROS_{it} \times UNF_{ROS_{it}}$ is the core explanatory variable in this paper, which indicates the degree to which tax inequity is reduced by tax enforcement system reform. In addition, this paper controls for firm age ($LnAge$), firm size ($LnSize$), leverage ratio ($LnLEV$), board size ($LnBSZ$), board independence (RID), and firm profitability (ROA). Year and industry fixed effects are also controlled for to eliminate the possible influence of year- and industry-invariant factors.

- 2) Using the tax enforcement agency reform represented by switching social insurance premium collection to the tax departments as the quasi-natural experiment:

$$TFP_{LP_{it}} = \alpha_0 + \alpha_1 \cdot ROI_{it} + \alpha_2 \cdot UNF_{ROI_{it}} + \alpha_3 \cdot ROI_{it} \times UNF_{ROI_{it}} + \alpha_4 \cdot LnAge_{it} + \alpha_5 \cdot LnSize_{it-1} + \alpha_6 \cdot LnLEV_{it-1} + \alpha_7 \cdot LnBSZ_{it-1} + \alpha_8 \cdot RID_{it-1} + \alpha_9 \cdot ROA_{it-1} + YearFE + IndustryFE + \varepsilon_{it} \quad (2)$$

where ROI_{it} is similarly used as the indicator for tax enforcement agency reform and $UNF_{ROI_{it}}$ indicates whether the firm suffered from tax inequity before the tax enforcement agency reform. $ROI_{it} \times UNF_{ROI_{it}}$ is the core explanatory variable in this paper, which indicates the degree to which tax inequity is reduced by tax enforcement agency reform.

4 Empirical results

4.1 Baseline regression

Table 5 reports the results of the baseline regressions on the impact of reduced tax inequity from tax enforcement reform on firms' sustainable development. Regression 1) demonstrates the impact of the reduction in tax inequity brought about by the tax enforcement system reform on the sustainable development of enterprises. The main explanatory variable $UNF_{ROS} \times ROS$ is

TABLE 9 Mediating mechanism of green invention patent applications.

Variables	Tax enforcement system reform			Tax enforcement agency reform		
	(1)	(2)	(3)	(4)	(5)	(6)
	TFP_LP	lnGIPA	TFP_LP	TFP_LP	lnGIPA	TFP_LP
lnGIPA	—	—	0.048*** (5.22)	—	—	0.052*** (5.70)
UNF_ROS	−0.353*** (−22.38)	−0.185*** (−5.66)	−0.346*** (−21.52)	—	—	—
ROS	−0.076** (−2.39)	0.088* (1.68)	−0.062* (−1.88)	—	—	—
UNF_ROS×ROS	0.130*** (5.88)	0.094** (2.33)	0.118*** (5.05)	—	—	—
UNF_ROI	—	—	—	−0.306*** (−15.66)	−0.065*** (−2.84)	−0.303*** (−15.51)
ROI	—	—	—	−0.080* (−1.66)	−0.074 (−1.33)	−0.076 (−1.59)
UNF_ROI×ROI	—	—	—	0.279*** (5.47)	0.119** (2.00)	0.273*** (5.36)
Controls	YES	YES	YES	YES	YES	YES
Constant	1.749*** (21.78)	−1.043*** (−7.67)	1.721*** (20.20)	1.744*** (21.41)	−1.020*** (−10.71)	1.797*** (21.95)
Observations	8,935	8,935	8,935	8,935	8,935	8,935
R-squared	0.769	0.581	0.771	0.759	0.542	0.760
Year FE	YES	YES	YES	YES	YES	YES
Ind FE	YES	YES	YES	YES	YES	YES

Note: ***, **, and * indicate that the estimates are significant at the 1%, 5%, and 10% levels, respectively. T-values are reported in parentheses.

significantly positive at the 1% level with a coefficient of 0.130, thus indicating that firms suffering from tax inequity experience a 13.0% more increase in enterprise sustainability after the reform compared to firms that did not suffer from tax inequity before it.

Regression 2) demonstrates the impact of the reduction in tax inequity brought about by tax enforcement agency reform on the sustainable development of enterprises. The main explanatory variable *UNF_ROI×ROI* is significantly positive at the 1% level with a coefficient of 0.279, thus indicating that firms that suffered from tax inequity experienced a 28.9% more increase in sustainability after the reform compared to firms that did not suffer from tax inequity before it.

The above results are consistent with the hypothesis that tax equity makes a significant contribution to the sustainable development of enterprises.

4.2 Robustness tests

4.2.1 Parallel trend test

The key assumption for the above regressions to provide causal inference is that the control group (i.e., firms that did not suffer

from tax inequity before the reform) provides an effective counterfactual for the sustainability of firms in the experimental group (i.e., firms that suffered from tax inequity before the reform). The basic premise for this assumption to hold is that the experimental and control groups satisfy the parallel trend condition. Moreover, considering that there may be a lag in the effect of tax enforcement reform and the possibility that the effect of reform may be affected by other related policies, this paper follows Beck et al. (2010) and Wang (2013) by constructing a more flexible DID model to allow the estimated coefficients to vary across years and thus examines the parallel trend before the reform as well as the dynamic effect after it.

$$TFP\_LP_{it} = \alpha_0 + \sum_{k=-16}^7 ROS_{it}^k + Controls + YearFE + IndustryFE + \varepsilon_{it} \quad (3)$$

$$TFP\_LP_{it} = \alpha_0 + \sum_{k=-16}^7 ROI_{it}^k + Controls + YearFE + IndustryFE + \varepsilon_{it} \quad (4)$$

Model (3)/(4) replaces ROS_{it}/ROI_{it} in Model (1)/(2) with the set of variables ROS_{it}^k/ROI_{it}^k , where k is the difference between the observation year and the year of reform implementation and takes

TABLE 10 Mediating mechanism of green utility model patent applications.

Variables	Tax enforcement system reform			Tax enforcement agency reform		
	(1)	(2)	(3)	(4)	(5)	(6)
	TFP_LP	lnGUPA	TFP_LP	TFP_LP	lnGUPA	TFP_LP
lnGUPA	—	—	0.037***	—	—	0.040***
	—	—	(3.49)	—	—	(3.70)
UNF_ROS	−0.353***	−0.054***	−0.352***	—	—	—
	(−22.38)	(−3.47)	(−22.33)	—	—	—
ROS	−0.076**	0.090***	−0.079**	—	—	—
	(−2.39)	(2.74)	(−2.47)	—	—	—
UNF_ROS×ROS	0.130***	0.054**	0.119***	—	—	—
	(5.88)	(2.39)	(5.84)	—	—	—
UNF_ROI	—	—	—	−0.306***	−0.006	−0.306***
	—	—	—	(−15.66)	(−0.31)	(−15.65)
ROI	—	—	—	−0.080*	−0.102**	−0.079*
	—	—	—	(−1.66)	(−2.18)	(−1.66)
UNF_ROI×ROI	—	—	—	0.279***	0.117**	0.228***
	—	—	—	(5.47)	(2.33)	(5.46)
Controls	YES	YES	YES	YES	YES	YES
Constant	1.749***	−0.608***	1.777***	1.744***	−0.806***	1.773***
	(21.78)	(−7.51)	(22.03)	(21.41)	(−10.28)	(21.68)
Observations	8,935	8,935	8,935	8,935	8,935	8,935
R-squared	0.769	0.496	0.769	0.759	0.401	0.759
Year FE	YES	YES	YES	YES	YES	YES
Ind FE	YES	YES	YES	YES	YES	YES

Note: ***, **, and * indicate that the estimates are significant at the 1%, 5%, and 10% levels, respectively. T-values are reported in parentheses.

the value of 0 if it is in the year of reform, n if it is the n th year of reform, and $-m$ if it is the m th year before the reform. In the sample period of this paper (2000–2019), the value of k takes the ranges of $[-16, 7]$ in Model (3) and $[-19, 21]$ in Model (4). Due to space limitations, this paper only presents the 5-year results before and after the reform implementation.

Table 6 reports the dynamic effects of the tax enforcement reform. Regressions 1–3 show the effects of the reform in the tax enforcement system. Companies are grouped according to whether they suffered from income tax inequity before the reform, with Regression 1 including the experimental group, Regression 2 including the control group and Regression 3 including the full sample. The results show that before the implementation of the tax enforcement system reform, the estimated coefficients are nonsignificant in all three groups. In the years after the implementation of the reform, there is a significant increase in sustainable development in the experimental group, while there is no significant impact in the control group. In the full sample group, ROS_{it}^k has a significant effect on corporate sustainability, but the coefficients are smaller than those of

the experimental group due to the inclusion of the control group sample. The above results indicate that the reform in the tax enforcement system has a dynamic long-term impact on the sustainable development of enterprises. Regressions 4–6 report the results of the dynamic regressions of the tax enforcement agency reform. The results are similar and indicate that the reform in tax enforcement agencies also has a dynamic long-term impact on the sustainable development of enterprises. Together, the above results verify the findings of the baseline regression.

4.2.2 Placebo test

To further rule out the concern that the increase in enterprise sustainability is a result of the tax enforcement reforms and not random, we conduct a placebo test by setting a pseudo-event time as a placebo during the years of the implementation of the tax enforcement reform. With the placebo replacing the year in which the treatment effect actually occurred, the experimental and control groups are re-selected based on the placebo year. The results reported in Table 7 reveal that the effects of the key variables in both Regressions 1 and

TABLE 11 Mediating mechanism of green invention patent grants.

Variables	Tax enforcement system reform			Tax enforcement agency reform		
	(1)	(2)	(3)	(4)	(5)	(6)
	TFP_LP	lnGIA	TFP_LP	TFP_LP	lnGIA	TFP_LP
lnGIA	—	—	0.039*** (2.92)	—	—	0.047*** (3.71)
UNF_ROS	−0.353*** (−22.38)	−0.135*** (−4.73)	−0.346*** (−20.58)	—	—	—
ROS	−0.076** (−2.39)	−0.004 (−0.10)	−0.058 (−1.58)	—	—	—
UNF_ROS x ROS	0.130*** (5.88)	0.080** (2.22)	0.125*** (4.78)	—	—	—
UNF_ROI	—	—	—	−0.306*** (−15.66)	−0.112*** (−2.64)	−0.289*** (−14.24)
ROI	—	—	—	−0.080* (−1.66)	−0.199* (−1.72)	−0.043 (−0.84)
UNF_ROI x ROI	—	—	—	0.279*** (5.47)	0.316*** (2.60)	0.232*** (4.27)
Controls	YES	YES	YES	YES	YES	YES
Constant	1.749*** (21.78)	−0.658*** (−7.80)	1.653*** (17.74)	1.744*** (21.41)	−0.948*** (−3.05)	1.718*** (19.82)
Observations	8,935	8,935	8,935	8,935	8,935	8,935
R-squared	0.769	0.484	0.768	0.759	0.550	0.760
Year FE	YES	YES	YES	YES	YES	YES
Ind FE	YES	YES	YES	YES	YES	YES

Note: ***, **, and * indicate that the estimates are significant at the 1%, 5%, and 10% levels, respectively. T-values are reported in parentheses.

$2(UNF\_ROS\_pb \times ROS\_pb / UNF\_ROI\_pb \times ROI\_pb)$ on enterprise sustainability are no longer significant, thus indicating that the increase in enterprise sustainability is indeed caused by the tax enforcement reforms and their resulting reduction in tax inequity—that is, the results of the main regressions are robust³.

4.2.3 Alternative dependent variable

The basic theory of economic growth states that the production function is $Y = A * f(K, L)$, and labor, capital, and technology are the basic factors that affect economic development. In the function, A represents the technology factor, L represents the labor input and K represents the

capital input. As a result, there are also three important core measures of sustainable development, namely, total factor productivity (which corresponds to the technology factor), labor intensity (which corresponds to the labor factor), and capital intensity (which corresponds to the capital factor).

In the main regression, the measure of enterprise sustainability is the total factor productivity (TFP) calculated using the LP method. To verify the robustness of the model and more comprehensively measure enterprise sustainability, the total factor productivity calculated using the OP method (TFP_OP), labor intensity (LAB), and capital intensity (CAP) are selected as alternative indicators of enterprise sustainability. Table 8 reports the regression results of the alternative indicators as explanatory variables, respectively, where Regressions 1, 3, and 5 test the effect of reduced tax inequity resulting from the reform of the tax enforcement system on the dependent variable, and Regressions 2, 4, and 6 test the effect of reduced tax inequity resulting from the reform of the tax enforcement agencies on the dependent variable. In all regressions, the main variables $UNF\_ROS \times ROS / UNF\_ROI \times ROI$ reveal a

³ The detailed method of assigning virtual years for the tax enforcement system reform is as follows. First, the regions are ranked in the order of provinces and municipalities in Table 1 (i.e., Chongqing, Shaanxi, ..., Guangdong, ..., Shanghai, etc.). As reform was carried out from 2013 to 2017, the virtual years between 2013 and 2017 are then assigned to the regions in the order of their rank, (e.g., Chongqing 2013; Shaanxi 2014;, Henan Province 2017; Inner Mongolia Autonomous Region 2013, ...). The method used to assign the virtual years of tax enforcement agency reform is similar.

TABLE 12 Mediating mechanism of green utility model patent grants.

Variables	Tax enforcement system reform			Tax enforcement agency reform		
	(1)	(2)	(3)	(4)	(5)	(6)
	TFP_LP	lnGUA	TFP_LP	TFP_LP	lnGUA	TFP_LP
lnGUA	—	—	0.037*** (4.10)	—	—	0.040*** (4.35)
UNF_ROS	−0.353*** (−22.38)	−0.065*** (−3.47)	−0.347*** (−21.76)	—	—	—
ROS	−0.076** (−2.39)	0.096** (2.43)	−0.062* (−1.90)	—	—	—
UNF_ROS x ROS	0.130*** (5.88)	0.072*** (2.65)	0.120*** (5.30)	—	—	—
UNF_ROI	—	—	—	−0.306*** (−15.66)	−0.214*** (−3.10)	−0.291*** (−14.45)
ROI	—	—	—	−0.080* (−1.66)	−0.122 (−0.73)	−0.058 (−1.15)
UNF_ROI x ROI	—	—	—	0.279*** (5.47)	0.305* (1.70)	0.245*** (4.60)
Controls	YES	YES	YES	YES	YES	YES
Constant	1.749*** (21.78)	−0.948*** (−9.96)	1.712*** (20.61)	1.744*** (21.41)	−2.219*** (−7.96)	1.705*** (19.98)
Observations	8,935	8,935	8,595	8,935	1,154	8,431
R-squared	0.769	0.082	0.771	0.759	0.165	0.760
Year FE	YES	YES	YES	YES	YES	YES
Ind FE	YES	YES	YES	YES	YES	YES

Note: ***, **, and * indicate that the estimates are significant at the 1%, 5%, and 10% levels, respectively. T-values are reported in parentheses.

significantly positive effect on the dependent variables, which indicates that the effect of tax equity on the sustainable development of enterprises is robust.

4.3 Mechanism analysis

To further examine the impact of tax equity on corporate sustainability, in this section, this paper empirically investigates the pathways through which tax equity affects corporate sustainability using green innovation as a mediating variable (Stewart, 1979; Schoenecker and Swanson, 2002; Andonova, 2003; Cano and Cano, 2006). In this paper, four indicators (green invention patent applications, utility model applications, invention patent grants, and utility model grants) are selected as measures of corporate green innovation. This paper adopts the causal steps approach to test for the mediating mechanism

effect (Judd & Kenny, 1981; Sobel, 1982; Baron and Kenny, 1986).

4.3.1 Green innovation applications

Green innovation applications represent the current green innovation output of enterprises, and green invention patent and utility model applications are selected as the metrics used in this paper. Among them, an invention patent refers to a new technical solution for a product, method or improvement, and a utility model refers to a new technical solution for a product shape, structure or combination thereof that is suitable for practical use. Table 9 reports the results of the empirical tests of the reduction in tax inequity brought about by the tax enforcement reform enacted through green invention patent applications.

Running Regressions 1 and 4 is the first step of the mediating mechanism effect test. The interaction terms are significant at the 1% level and the coefficients are positive, which indicates that the reduction in tax inequity brought about by tax enforcement

TABLE 13 Heterogeneity tests for different life cycle stages.

Variables	Young firms		Mature firms	
	(1)	(2)	(3)	(4)
	TFP_LP	TFP_LP	TFP_LP	TFP_LP
ROS	−0.038 (−0.72)	—	−0.134*** (−3.26)	—
UNF_ROS	−0.342*** (−17.40)	—	−0.381*** (−14.38)	—
UNF_ROS×ROS	0.208*** (5.26)	—	0.133*** (4.20)	—
ROI	—	0.033 (0.37)	—	−0.134** (−2.36)
UNF_ROI	—	−0.281*** (−10.19)	—	−0.333*** (−12.09)
UNF_ROI×ROI	—	0.156* (1.69)	—	0.342*** (5.53)
Controls	YES	YES	YES	YES
Constant	1.382*** (11.32)	1.512*** (12.09)	2.034*** (17.79)	1.924*** (16.81)
Observations	4,278	4,278	4,656	4,656
R-squared	0.776	0.765	0.761	0.751
Year FE	YES	YES	YES	YES
Ind FE	YES	YES	YES	YES

Note: ***, **, and * indicate that the estimates are significant at the 1%, 5%, and 10% levels, respectively. T-values are reported in parentheses.

reform significantly contributes to the sustainable development of enterprises. In Regressions 2 and 5, the interaction terms are significant at the 5% level and the coefficients are 0.094 and 0.119, respectively, thus indicating that the reduction in tax inequity brought about by tax enforcement reform increases green invention patent applications by approximately 10%. In Regressions 3 and 6, the coefficients on $\ln GIPA$ are significantly positive at the 1% level, which indicates that there is a significantly positive relationship between green invention patent applications and the sustainable development of enterprises. Meanwhile, the coefficients on the interaction term are significant at the 1% level, but less so than their counterparts in Regressions 1 and 3, thus indicating that green invention patent applications partially mediate the relationship between tax equity and the sustainable development of enterprises.

Table 10 reports the results of the empirical tests on how the reduction in tax inequity brought about by tax enforcement reform affects sustainable development through green utility model applications. Similarly, green utility model applications exhibit a partial mediating pattern in the relationship between tax equity and sustainable development.

4.3.2 Green innovation grants

A patent application indicates that a company has made an invention and applied for authorization from the intellectual property department. However, whether the final authorization is granted depends on whether the patent meets the corresponding requirements. In other words, patent grants are a better indicator of an enterprise's ability to innovate than patent applications. Based on this, this paper also tests the mediating effects of the number of green invention patents and utility models that have been granted.

Table 11 reports the results of the empirical tests on the mediating effect of green invention model patent grants. In Regressions 1 and 4, the coefficients on the interaction terms $UNF\_ROS \times ROS$ and $UNF\_ROI \times ROI$ are both significant and positive at the 1% level, thus indicating that tax equity positively affects enterprise sustainability; in Regressions 2 and 5 the interaction terms remain significantly positive, which indicates that tax equity increases the number of green invention patent grants; in Regressions 3 and 6, $\ln GIPA$ has a positive coefficient at the 1% level, which indicates that green invention patent grants promote sustainable development. The interaction terms, although significant at the 1% level, have smaller coefficients than their counterparts in Regressions 1 and 4, thus indicating that green invention patent grants partially mediate the effect of tax equity on sustainable development.

Table 12 reports the results of the empirical tests on how the reduction in tax inequity brought about by tax enforcement reform affects sustainable development through green utility model grants. Similarly, green utility model grants exhibit a partial mediating pattern in the relationship between tax equity and sustainable development.

4.4 Heterogeneity analysis

The actions taken by firms differ depending on their maturity and the market environment in which they operate. Thus, theoretically, the effects of changes in tax equity on the sustainable development of enterprises may differ between firms in different life cycle stages and market environments. To identify the heterogeneous effects of tax equity on enterprise sustainability more precisely, this paper conducts empirical tests from the following two aspects.

4.4.1 Life cycles

Firms at different life cycle stages have different tax sensitivities and therefore respond differently to changes to the tax regime. Based on this, the paper groups the sample according to firm age. Those above the average age are defined as mature firms and those below the average age are defined as young firms. Table 13 reports the regression results of the heterogeneity tests. The coefficients on $UNF\_ROS \times ROS$ / $UNF\_ROI \times ROI$ are significantly positive at the 1% level in all

TABLE 14 Heterogeneity tests for different market environments.

Variables	Unfavorable market environment		Favorable market environment	
	(1)	(2)	(3)	(4)
	TFP_LP	TFP_LP	TFP_LP	TFP_LP
ROS	−0.076 (−1.62)	—	−0.032 (−0.57)	—
UNF_ROS	−0.316*** (−14.03)	—	−0.380*** (−16.88)	—
UNF_ROS x ROS	0.060* (1.69)	—	0.174*** (5.92)	—
ROI	—	−0.027 (−0.41)	—	−0.111 (−1.57)
UNF_ROI	—	−0.197*** (−6.74)	—	−0.386*** (−14.40)
UNF_ROI x ROI	—	0.164** (2.32)	—	0.376*** (5.02)
Controls	YES	YES	YES	YES
Constant	1.756*** (14.77)	1.742*** (14.27)	1.725*** (15.57)	1.754*** (15.94)
Observations	3,908	3,908	5,027	5,027
R-squared	0.756	0.743	0.785	0.778
Year FE	YES	YES	YES	YES
Ind FE	YES	YES	YES	YES

Note: ***, **, and * indicate that the estimates are significant at the 1%, 5%, and 10% levels, respectively. T-values are reported in parentheses.

regressions, thus indicating that reducing tax inequities significantly contributes to enterprise sustainability irrespective of age. Furthermore, the coefficient on $UNF\_ROS \times ROS$ is significantly larger in the group of young firms than it is in the group of mature firms, which indicates that the reduction in tax inequity brought about by tax enforcement reform promotes sustainable development to a greater degree in young firms; the coefficient on $UNF\_ROI \times ROI$ is larger for mature firms than it is for young firms, which indicates that the reduction in tax inequity brought about by tax enforcement agency reform promotes sustainable development to a greater degree in mature firms. This may be due to the fact that reforming the tax enforcement system breaks down intradepartmental information barriers and is therefore more effective in reducing information asymmetries on the enforcement side and preventing rent-seeking behaviors among enforcement agencies. While young enterprises have fewer social connections and are more likely to suffer from tax inequities resulting from tax enforcement, they benefit more from tax enforcement system reform. Reforming tax enforcement agencies reduces information asymmetries on the payment side by coordinating social security contributions and tax payments and thus discourages tax evasion. Since mature enterprises are generally more disciplined in paying social

security contributions, they are more likely to benefit from the tax equity brought about by tax enforcement agency reform.

4.4.2 Market environment

A favorable market environment is more protective of inventions and more conducive to the transformation of patented technologies into tangible output, so the market environment has an important impact on the sustainable development of enterprises. Therefore, this paper incorporates the marketization index to observe the heterogeneous impact of reduced tax inequities on the sustainable development of enterprises under different marketization conditions.

Table 14 reports regression results. In both the unfavorable and the favorable market environment subgroups, the coefficients on $Reform_{it} \times Inequity_i$ are all significantly positive. This indicates that the reduction in tax inequity brought about by tax enforcement reform significantly contributes to the sustainable development of enterprises regardless of the market environment. Furthermore, this paper finds that the coefficients on $UNF\_ROS \times ROS / UNF\_ROI \times ROI$ are larger in the regressions on the favorable market environment subgroup. This indicates that tax equity can better promote the sustainable development of enterprises in areas with a favorable market environment.

5 Conclusion

Sustainable development, which represents a form of economic growth with environmental friendliness as its main feature, is becoming an urgent priority as environmental pollution and resource scarcity are becoming increasingly serious problems. However, the positive environmental externalities associated with sustainable development impose an additional cost burden on enterprises, which makes sustainable development difficult to enforce through market regulation. The key to stimulating sustainable development is to convert its positive environmental externalities into corporate income through taxation policies. Establishing a fair tax regime enhances the credibility of tax law and its enforcement, which are essential prerequisites for tax policies to have the desired effect.

This paper takes a sample of Chinese listed companies between 2000 and 2019 and constructs DID models using two types of tax reform as quasi-natural experiments—namely, tax enforcement system reform and tax enforcement agency reform—as they are both important pathways for promoting tax equity. The paper finds through empirical research that tax equity has a facilitating effect on the sustainable development of enterprises and that promoting green innovation has a mediating effect.

Furthermore, tax equity promotes sustainable development to a greater degree in favorable market environments, mainly because they are more conducive to the protection and transformation of green innovation. Tax enforcement system reform has a more pronounced effect on young firms, while tax enforcement agency reform has a more pronounced effect on mature firms, mainly because young firms are more vulnerable to tax inequities that originate from the enforcement side. However, mature firms can benefit more from increased tax equity on the payment side.

Based on the above findings, this paper draws the following conclusions. 1) Corporate sustainable development has “double environmental externalities,” and the mismatch between benefits and costs is the main obstacle to enterprises adoption of sustainable development strategies. 2) Tax enforcement reform begins with relieving information asymmetries and achieving a balance between the “fairness” of taxation and the “efficiency” of sustainable economic development; doing so enables the government to encourage green innovation and promote sustainable economic development through taxation policy. 3) A favorable market environment is an important prerequisite

for tax equity to be able to promote sustainable development, mainly because it offers better protection for the intellectual property rights associated with green innovation and is also conducive to the transformation of green innovation into tangible output. 4) Different types of tax enforcement reforms have different impacts on the sustainable development of enterprises at different life cycle stages, mainly because they suffer from different types of tax inequity. Therefore, different tax policies should be adopted for enterprises at different life cycle stages to internalize the positive externalities of green innovation. 5) In the parallel trend test, we find that the positive effect of tax enforcement reform on the sustainable development of enterprises first increases and then gradually decreases, which indicates that policy reform cannot immediately achieve its objectives and thus needs to be continuously and consistently promoted (Fan et al. 2001).

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: <https://cn.gtadata.com/https://www.cnipa.gov.cn/>.

Author contributions

WW designed the study, performed the statistical analysis, and wrote the draft of the manuscript.

Conflict of interest

Author WW was employed by the company Hundsun Technologies Inc.

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Does ESG performance promote total factor productivity? Evidence from China

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Currently, environmental, social, and corporate governance (ESG) has become an all-pervasive term in the industrial sector, owing to its significant impact on corporate decision-making. While most of the studies provide evidence that the ESG significantly improves a firm's performance and value in the long run, few studies quantitatively analyzed the linkage between ESG and total factor productivity (TFP). Using the data of Chinese-listed companies during 2010–2020, we found that there is a positive relationship between ESG performance and TFP. ESG also improves the corporate TFP by reducing the financial constraints and improving the innovation input. Our extended analysis revealed that this beneficial effect tends to be stronger for SOEs (state-owned enterprises) and industries with high pollution levels. This study also brought to light some implications for Chinese firms in relation to their ESG practices and sustainable development.

KEYWORDS

ESG performance, total factor productivity, financial constraints, R&D investment, corporate sustainable development

Introduction

Environmental, social, and corporate governance are abbreviated as ESG, which was proposed by the United Nations (UN) in 2004. In recent years, the issues of sustainability and ESG activities are getting growing attention. For example, [Lins et al. \(2017\)](#) investigated the performance of ESG firms during periods when the trust in corporations was at its low ebb. They arrived at the conclusion that firms that have ESG show higher performance and fetch higher returns than firms that lack ESG. [Bruna et al. \(2022\)](#) and [Huang et al. \(2022\)](#) noted that the enterprise's ESG strategies have a positive and significant impact on the enterprise value and financial performance. In emerging and developing countries, especially, ESG reduces the cost of capital and increases the value of companies ([Wong et al., 2021](#)). Meanwhile, any adverse ESG information also has a significant positive impact on the evaluation of enterprises ([Wong and Zhang, 2022](#)). ESG's importance in enterprises is steadily increasing and is gradually being applied to the process of enterprise governance, such as agency costs ([Lambert et al., 2007](#)), investment efficiency ([Zhong and Gao, 2017](#)), financial constraints ([Fafaliou et al., 2022](#)), cost of capital ([Cheng et al., 2014](#); [Capelle-Blancard and Petit, 2019](#)), cost of debt ([Gerwanski, 2020](#)), and innovation capabilities of enterprises ([Broadstock et al., 2021](#)). The findings highlight the fact that the effect caused by firms' ESG has a long provenance in financial economics and enterprise governance.

With a continuous implementation of China's sustainable development strategy, the economy is shifting to the stage of high-quality development. Improving total factor productivity (TFP) is the best way to promote high-quality economic growth (Glawe and Wagner, 2019). TFP is an important indicator of enterprise production efficiency (Schoar, 2002; Barth et al., 2005) and a key determinant of the enterprise value (Tian and Twite, 2011). As a pillar of economy, TFP plays a crucial role in promoting corporate sustainable development. The previous literature examined the factors influencing TFP from the perspective of internal and external corporate governance. TFP is mainly influenced by financial constraints (Caggese and Cunat, 2013), R&D (Research and Development) (Sheu and Yang, 2005; Chiang and Lin, 2007), uncertainty in economic policies (Li et al., 2021), digital financial inclusion (Chen et al., 2022), value-added tax reforms (Peng et al., 2021), and so on. However, limited attention has been paid to the mechanism of ESG performance and TFP. In this context, what exactly is the impact of ESG on TFP? How does ESG affect TFP? The present study discusses the above two aspects to explore the factors affecting the change in total factor productivity (TFP).

We empirically studied the impact of ESG on TFP using data from Chinese-listed companies. Our sample includes 15,757 firm-year observations from 2010 to 2020. The data are derived from the China Stock Market & Accounting Research (CSMAR) database. We investigated whether ESG is related to TFP or not. We studied the potential channels whose technological innovation and financial constraints have an effect on the TFP by the mediating effect. We found that the ESG can significantly increase the TFP. The analyses of endogeneity, self-selection bias, and robustness tests support our conclusions further. From the mediating effect analysis, ESG increases TFP by enhancing the innovation capacity of enterprises and easing their financial constraints. From further analyses, we found that this significant effect is stronger among state-owned enterprises (SOEs) and heavy pollution firms.

The present study offers three major contributions to the research on ESG, which are given as follows: first, our research discusses the impact of ESG on TFP, enriching the existing literature on the influence of ESG. The existing literature focuses on the impact of ESG on the firm value (Azmi et al., 2021; Wong et al., 2021; Bofinger et al., 2022), idiosyncratic risk (He et al., 2022), financial risk (Shakil, 2021), cash flow (Gregory, 2022), default risk (Li et al., 2022), and costs of raising capital (Luo, 2022). However, the impact of ESG on TFP has not been given due attention. Second, our results indicate that ESG has a positive impact on TFP through the mediating effect of innovation capacity and financial constraints and contribute to the understanding of TFP. Given the significant impact of ESG on corporate governance, our research highlights the importance of ESG in corporate sustainable development.

The remaining of the present study is organized as follows. The next section shows a review of the literature

and the hypotheses proposed. In the third section of research design, data, variables, and model design are described. In the fourth section, the empirical results, the robustness tests, and heterogeneity analysis are present. The final section presents the conclusion of the present study.

Literature review and hypotheses development

ESG performance and total factor productivity

In recent years, environmental, social, and governance (ESG) is increasingly involved in planning and implementing corporate strategies (Durand et al., 2019; Huang et al., 2022). Hence, an increasing number of scholars and managers are beginning to pay extra attention to the impact of sustainability strategy on corporate performance (Margolis and Walsh, 2003; Shen and Chang, 2009; Fiandrino et al., 2019; Li et al., 2019). In addition, several bodies of literature have documented the positive impact of ESG strategies on a firm's performance, such as financial performance (Rettab et al., 2009; Hernández et al., 2020), innovation (Inigo and Albareda, 2019), financial constraints (Samet and Jarbouï, 2017), and corporate reputation (Liu et al., 2014). At the same time, these factors affect TFP even further. TFP is an effective indicator to measure an enterprise's performance (Barth et al., 2005; Tian and Twite, 2011).

The existing literature suggests several possible channels through which ESG performance has a positive impact on total factor productivity. First, a high-quality ESG performance helps a firm to increase the steps taken toward innovation in the process of firm operation and development. The impact of promoting corporate social responsibility (CSR) activities on corporate performance originates from the enhancement of R&D (Research & Development) efforts (Lioui and Sharma, 2012), which too has a significant positive impact on TFP (Sheu and Yang, 2005; Chiang and Lin, 2007). A firm's ESG strategy initially enhances its ability to pursue innovative activities and then ultimately and positively impacts its financial/operational performance (Broadstock et al., 2021), thus improving the TFP of enterprises (Chang and Tang, 2021). Second, firms with a high-quality ESG performance are more effective in mitigating financial constraints and increasing TFP. Firms with a good performance of ESG have a lower default risk, lower financing costs, and higher cash holdings of enterprises (Li et al., 2022). For corporate managers, ESG is a good tool that reduces the cost of raising capital in the capital markets (Luo, 2022), which in turn enhance the firm's TFP. This leads to the first hypothesis.

Hypothesis 1. There is a positive association between ESG performance and total factor productivity (TFP).

ESG performance, state ownership, and total factor productivity

ESG has become an important standard for the international community to measure the level of green and sustainable development of enterprises. Some people believe that environmental and social issues should be managed only by governments, and not companies, because governments alone are more capable of tackling such overwhelming issues. There are some differences between state-owned enterprises (SOEs) and non-state-owned enterprises with regard to business operation, management structure, and external environment. Hsu et al. (2021) considered firms from 45 countries that include state ownership companies. Their results showed that state-owned firms play a greater role and are more engaged in environmental and social issues than other firms and are even concentrated in energy firms and firms in emerging economies. Franceschelli et al. (2019) confirmed that ESG has a positive effect on an SOE's financial performance. Thus, the beneficial effect tends to be stronger for SOEs than for non-SOEs. This leads to the second hypothesis.

Hypothesis 2. The effect of ESG on TFP tends to be more evident for SOEs than for non-SOEs.

ESG performance, pollution, and total factor productivity

Environment has a profound impact on TFP, which serves as an important indicator of enterprise development. Environmental regulation presents a positive effect on TFP (Ai et al., 2020) and shows a much greater influence on heavy pollution industries when compared with non-heavy pollution industries (Yang et al., 2022). In heavy pollution industries, environmental regulation reduces the ability of the enterprise to introduce novel technological innovations (Shen et al., 2019). In addition, Doshi et al. (2013) found that heavy pollution enterprises face higher financing costs. In that case, better ESG engagement alone encourages heavy pollution enterprises to pursue R&D investment and decrease consequent financial constraints. Besides, for sustainable development, enterprises will further increase the disclosure of ESG information. Resource disclosure of ESG information will increase the free cash flow of an enterprise, decrease the financing cost (Plumlee et al., 2015), and increase the ability to bring in technological innovation. Thus, the beneficial effect of linking environmental regulation and TFP, which entails a decrease in cost factor, tends to be stronger for heavy pollution enterprises than for non-heavy pollution enterprises. This leads to the third hypothesis.

Hypothesis 3. The effect of ESG on TFP tends to be even more evident for heavy pollution enterprises than for non-heavy pollution enterprises.

Data and research design

Data

In our study, we used the data of Chinese A-share-listed firms during the period 2010–2020. All financial data, ESG data, and TFP data were obtained from the China Stock Market and Accounting Research (CSMAR) database. The year 2010 was chosen as the beginning year of the sample period. The samples were screened according to the following criteria: (1) Financial firms and insurance firms were excluded from the sample; (2) the special treatment (ST and ST*) firms were excluded; and (3) the variables were winsorized at both the top and bottom 1% quantiles to reduce the potential impact of outliers. Following these criteria, the final sample comprised 15,757 firm-year observations.

Empirical design

To investigate the effect of ESG performance on TFP, we used the following model:

$$TFP_{i,t} = \alpha + \beta_1 ESG_{i,t} + \sum Control_{i,t} + Industry + Year + \varepsilon_{i,t}, \quad (1)$$

where for firm i and year t , the dependent variable is total factor productivity TFP, which is measured by the LP method (Levinsohn and Petrin, 2003). We also followed the method of Olley and Pakes (1996) to calculate the (log) level of TFP of firm i at year t using the non-parametric method to proxy TFP in the robustness test. The independent variable is ESG performance. Following Lin et al. (2021), we employed the ESG index to proxy ESG performance and transfer the ESG rating from AAA to C to numbers 1 to 9. A higher number in ESG rating means a higher ESG performance. This index has been developed by the Sino-Securities Index Information Service (Shanghai) Co. Ltd. for all listed firms in China.

The control variables Control include firm size (Size), return on assets (ROA), leverage (Lev), growth opportunity (Growth), and firm age (FirmAge). To compute the characteristics of corporate governance, we included the percentage of independent directors (Indep), duality of the chairman and CEO (Dual), the shareholding ratio of the top shareholder (Top1), and whether the firm is a state-owned firm (SOE). In addition, the industry and year are included in the model.

To test the mediating effect of financial constraint and R&D on the relationship between the ESG and the TFP, we estimated the following regression:

$$KZ(RD)_{i,t} = \alpha + \beta_1 ESG_{i,t} + \sum Control_{i,t} + Industry + Year + \varepsilon_{i,t} \quad (2)$$

TABLE 1 Summary statistics.

Variable	N	mean	sd	min	median	max
<i>TFP_{lp}</i>	15,757	16.317	1.086	12.954	16.2	20.518
<i>ESG</i>	15,757	6.444	1.131	1	6	9
<i>Size</i>	15,757	22.24	1.249	19.525	22.068	26.398
<i>ROA</i>	15,757	0.041	0.07	−0.398	0.041	0.244
<i>Lev</i>	15,757	0.416	0.198	0.027	0.41	0.925
<i>Growth</i>	15,757	0.177	0.401	−0.66	0.117	4.33
<i>Cash</i>	15,757	0.049	0.066	−0.2	0.047	0.257
<i>FirmAge</i>	15,757	2.84	0.351	1.099	2.89	3.555
<i>Indep</i>	15,755	0.376	0.054	0.273	0.364	0.6
<i>Dual</i>	15,757	0.311	0.463	0	0	1
<i>Top1</i>	15,757	0.336	0.146	0.083	0.315	0.758
<i>SOE</i>	15,757	0.257	0.437	0	0	1

$$TFP_{i,t} = \alpha + \beta_1 ESG_{i,t} + \beta_2 KZ(RD)_{i,t} + \sum Control_{i,t} + Industry + Year + \varepsilon_{i,t}, \quad (3)$$

where $KZ(RD)_{i,t}$ represents the mediating variable. KZ is the mediating variable, and we used the KZ index as a quantitative indicator to measure the degree of financial constraint of the listed firm. The other mediating variable is the R&D intensity RD, which is measured by the ratio of R&D investment to operating income. Appendix A provides definitions of all variables that are used in our analysis.

Empirical results and analysis

Descriptive statistics

Table 1 presents the descriptive statistics for the key variables. The mean value of TFP is 16.317, the standard deviation is 1.086, the maximum value is 20.518, and the minimum value is 12.954, which demonstrate that TFP is different among sample firms, but it is a normal distribution. The mean value of ESG is 6.444, which demonstrates that the level of ESG is between BBB and A. From Table 1, the average firm has a level of total assets (*Size*) of 22.24, *ROA* has an average (median) of 4.1% (4.1%), while the leverage (*Lev*) has a mean (median) of 0.416 (0.41). In addition, the firms of the sample have an average annual sales growth (*Growth*) of 0.177 and an average sum of cash scaled by total assets (*Cash*) of 0.049.

Basic regression results

The impact of ESG on TFP

First, the main results, which show the influence of ESG on TFP, are discussed in Table 2. The control variables, year

and industry effects, were added in eq. (1). The coefficient of ESG is 0.289 at the 1% significance level in Column (1), indicating that the ESG increases the TFP significantly. When we added the control variables only, Column (2) shows that the coefficient of ESG is 0.0019 at the 1% significance level. After controlling for both the year and industry effects, as shown in Column (3) of Table 2, the coefficient of ESG is 0.023 at the 1% significance level in Column (3), indicating that the ESG increases the TFP significantly. This proves Hypothesis 1. For the control variables, the results in Table 2 show that firm's size, ROA, Lev, Growth, and Cash are significantly and positively related to TFP.

Heterogeneity analysis

SOEs vs. non-SOEs

In China, the actual situation in which state-owned enterprises (SOEs) are different from non-state-owned enterprises in terms of ESG needs to be taken into consideration. The state-owned firms are more engaged in environmental and social issues than other non-state-owned firms (Hsu et al., 2021). Meanwhile, ESG has a positive influence on a firm's financial performance (Franceschelli et al., 2019).

The sample is divided into SOEs and non-SOEs. From the regression model (1), we established whether the impact of ESG on the TFP is going to be relatively different in different ownership types. In Columns (1) and (2) of Table 3, the regression results demonstrate that ESG in SOEs can play a much better role in increasing TFP than those in non-SOEs. From the above results, Hypothesis 2 is verified.

TABLE 2 The effect of environmental, social, and corporate governance (ESG) on total factor productivity (TFP).

Variable	TFP _{lp}		
	(1)	(2)	(3)
ESG	0.289*** (39.620)	0.019*** (4.308)	0.023*** (5.192)
Size		0.640*** (136.342)	0.636*** (131.860)
ROA		1.823*** (23.243)	1.867*** (23.715)
Lev		0.941*** (32.215)	0.947*** (32.316)
Growth		0.110*** (9.409)	0.121*** (10.288)
Cash		0.632*** (8.566)	0.569*** (7.648)
FirmAge		0.024* (1.778)	−0.003 (−0.225)
Indep		−0.147* (−1.772)	−0.159* (−1.919)
Dual		−0.019* (−1.908)	−0.025** (−2.455)
Top1		0.166*** (5.179)	0.171*** (5.330)
SOE		0.009 (0.735)	0.014 (1.177)
Constant	14.455*** (302.977)	1.383*** (13.824)	1.516*** (14.234)
Year	No	No	Yes
Indu	No	No	Yes
N	15,757	15,755	15,755
r ²	0.091	0.738	0.801

The t-statistics reported in parentheses are based on standard errors clustered at the firm level. ***, **, and * denote significance at the 1, 5, and 10% levels, respectively.

TABLE 3 Heterogeneity analysis.

Variable	TFP _{lp}			
	nonSOE (1)	SOE (2)	non heavy pollu (3)	heavy pollu (4)
ESG	0.006* (1.669)	0.022*** (3.652)	0.004 (1.096)	0.015*** (3.107)
Size	0.553*** (69.170)	0.595*** (45.953)	0.580*** (70.730)	0.445*** (36.671)
ROA	0.688*** (12.734)	1.997*** (16.781)	0.787*** (14.157)	1.132*** (12.650)
Lev	0.360*** (11.451)	0.363*** (6.680)	0.459*** (13.840)	0.215*** (4.874)
Growth	0.171*** (23.489)	0.166*** (12.690)	0.166*** (22.197)	0.194*** (16.890)
Cashflow	0.758*** (14.078)	0.364*** (4.244)	0.637*** (11.536)	0.724*** (9.812)
FirmAge	0.263*** (5.596)	0.118 (1.488)	0.282*** (6.046)	0.299*** (4.333)
Indep	−0.107 (−1.204)	0.069 (0.604)	0.069 (0.807)	−0.186 (−1.635)
Dual	−0.025*** (−2.674)	−0.007 (−0.387)	−0.028*** (−2.833)	0.000 (0.006)
Top1	−0.076 (−1.397)	−0.178** (−2.273)	−0.147*** (−2.612)	−0.050 (−0.708)
SOE			0.012 (0.540)	0.020 (0.618)
_cons	3.075*** (15.397)	2.446*** (7.118)	2.440*** (11.928)	5.271*** (17.810)
Year	Yes	Yes	Yes	Yes
Indu	Yes	Yes	Yes	Yes
N	11,701	4,054	11,274	4,481
r ²	0.658	0.646	0.658	0.622

The t-statistics reported in parentheses are based on standard errors clustered at the firm level. ***, **, and * denote significance at the 1, 5, and 10% levels, respectively.

Heavy pollution enterprises vs. non-heavy pollution enterprises

Environment has a significant impact on TFP. Heavy pollution enterprises have a lower ability of introducing technological innovations in their enterprises (Shen et al., 2019) and thereby face higher financing costs, according to Doshi et al. (2013). Heavy pollution enterprises have to first strengthen the disclosure of ESG information so as to alleviate financial constraints (Luo, 2022), promote technological innovation (Broadstock et al., 2021), and thus have a positive impact on TFP. From Columns (3) and (4) of Table 3, the regression results show that ESG in heavy pollution enterprises has to play a more important role in increasing TFP than non-heavy pollution enterprises. Therefore, hypothesis 3 is verified.

Mechanism analysis

The mediating effect of financial constraints and technological innovation

With the continuous implementation of the sustainable development strategy, the disclosure of ESG information becomes particularly important from the enterprises' value point of view. ESG can alleviate the financial constraints of enterprises (Samet and Jarbou, 2017), improve the innovation ability of enterprises (Inigo and Albareda, 2019), and then augment the TFP. Furthermore, we examined the mediating role of technological innovation and financial constraints underlying the effect of ESG on TFP. In Table 4, from Column (1), the coefficient of ESG is 0.023 at the 1% significance level, which is

TABLE 4 Mechanism analysis.

Variable	<i>TFP_{1p}</i> (1)	<i>KZ</i> (2)	<i>TFP_{1p}</i> (3)	<i>TFP_{1p}</i> (4)	<i>RD</i> (5)	<i>TFP_{1p}</i> (6)
<i>ESG</i>	0.023*** (5.192)	−0.020** (−1.999)	0.022*** (5.104)	0.023*** (5.192)	0.001*** (8.415)	0.016*** (3.802)
<i>KZ</i>			−0.020*** (−5.872)			
<i>RD</i>						4.292*** (21.743)
<i>Size</i>	0.636*** (131.860)	−0.254*** (−22.300)	0.631*** (128.934)	0.636*** (131.860)	−0.003*** (−17.969)	0.651*** (135.553)
<i>ROA</i>	1.867*** (23.715)	−5.433*** (−29.242)	1.759*** (21.787)	1.867*** (23.715)	0.023*** (7.201)	1.770*** (22.782)
<i>Lev</i>	0.947*** (32.316)	6.740*** (97.494)	1.080*** (29.146)	0.947*** (32.316)	−0.006*** (−4.982)	0.972*** (33.634)
<i>Growth</i>	0.121*** (10.288)	−0.294*** (−10.618)	0.115*** (9.767)	0.121*** (10.288)	0.001 (1.197)	0.118*** (10.234)
<i>Cashflow</i>	0.569*** (7.648)	−14.744*** (−83.936)	0.277*** (3.097)	0.569*** (7.648)	0.023*** (7.653)	0.472*** (6.424)
<i>FirmAge</i>	−0.003 (−0.225)	0.214*** (6.154)	0.001 (0.063)	−0.003 (−0.225)	−0.007*** (−12.008)	0.027* (1.845)
<i>Indep</i>	−0.159* (−1.919)	0.674*** (3.446)	−0.146* (−1.759)	−0.159* (−1.919)	0.008** (2.366)	−0.192** (−2.357)
<i>Dual</i>	−0.025** (−2.455)	−0.110*** (−4.652)	−0.027*** (−2.673)	−0.025** (−2.455)	0.002*** (4.690)	−0.033*** (−3.302)
<i>Top1</i>	0.171*** (5.330)	−0.713*** (−9.438)	0.156*** (4.880)	0.171*** (5.330)	−0.015*** (−11.587)	0.234*** (7.386)
<i>SOE</i>	0.014 (1.177)	0.285*** (10.179)	0.020* (1.649)	0.014 (1.177)	−0.000 (−0.043)	0.014 (1.202)
<i>Constant</i>	1.516*** (14.234)	3.851*** (15.326)	1.592*** (14.856)	1.516*** (14.234)	0.103*** (24.350)	1.073*** (10.038)
<i>Year</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Indu</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	15,755	15,755	15,755	15,755	15,755	15,755
<i>r2</i>	0.741	0.703	0.742	0.741	0.098	0.749

The t-statistics reported in parentheses are based on standard errors clustered at the firm level. ***, **, and * denote significance at the 1, 5, and 10% levels, respectively.

consistent with the basic regression results. From Column (2), the coefficient of ESG is −0.020 at the 1% significance level. In Column (3), we added the ESG and financial constraints in our model and found that the coefficient of ESG is positive and significant at the 1% significance level and that the coefficient of financial constraints is negative and significant at the 1% significance level. It shows that ESG increases TFP by easing financial constraints. Columns (4)–(6) show the results that the mediating variable is a technological innovation. From Column (5), the coefficient of ESG is 0.001 at the 1% significance level. In Column (6), the ESG and technological innovation are added to our model, and the coefficient of ESG and

technological innovation are positive and significant at the 1% significance level. It shows that ESG increases TFP by promoting technological innovation.

Endogeneity issues and robustness test

In the present study, an investigation on the relationship between ESG and TFP showed that it may be affected by other unobservable factors, which may result in endogeneity problems. To address the potential endogeneity issue, we performed TFP lags by one-stage, propensity score matching

TABLE 5 Endogeneity issues.

Panel A: The One-phase-lagged of Total Factor Productivity (TFP)/Firm fixed effects model/ Propensity score matching (PSM)

Variable	<i>L.TFP_lp</i> (1)	<i>TFP_lp</i> (2)	<i>TFP_lp</i> (3)
ESG	0.020*** (4.340)	0.008*** (2.663)	0.012*** (2.911)
Size	0.639*** (118.380)	0.546*** (80.750)	0.641*** (130.209)
ROA	1.434*** (17.002)	0.902*** (18.994)	2.248*** (25.830)
Lev	0.911*** (28.001)	0.368*** (13.790)	0.875*** (28.733)
Growth	−0.510*** (−37.697)	0.172*** (27.383)	0.107*** (9.115)
Cashflow	0.677*** (8.063)	0.642*** (14.283)	0.743*** (9.903)
FirmAge	−0.003 (−0.204)	0.303*** (7.763)	0.017 (1.144)
Indep	−0.196** (−2.150)	−0.092 (−1.328)	−0.258*** (−3.189)
Dual	−0.016 (−1.419)	−0.016** (−2.034)	−0.034*** (−3.430)
Top1	0.183*** (5.124)	−0.141*** (−3.190)	0.192*** (6.123)
SOE	0.008 (0.611)	0.007 (0.365)	0.066*** (5.799)
Constant	1.586*** (13.139)	3.117*** (12.438)	1.083*** (8.496)
Year	Yes	Yes	Yes
Indu	Yes	Yes	Yes
N	12,473	15,755	12,842
r2	0.744	0.677	0.810

Panel B: Instrumental variables (IV) approach

	ESG (1)	<i>TFP_lp</i> (2)
ESG		0.039*** (2.935)
IV	0.866*** (75.614)	
Control	Yes	Yes
Year	Yes	Yes
Indu	Yes	Yes
N	15,755	15,755
F-statistics	80.451	

The t-statistics reported in parentheses are based on standard errors clustered at the firm level. ***, **, and * denote significance at the 1, 5, and 10% levels, respectively.

(PSM) procedure, firm fixed-effects model, and instrumental variables (IV) approach.

The one-phase-lagged of TFP

To solve the endogeneity issue, the present study adopted the method of lagging the dependent variable by one period. Column (1) of Table 5 show that the coefficient of ESG is 0.020 at the 1% significance level. The results are consistent with those given previously.

Firm fixed-effect model

To mitigate potential problems that arise from omitting time-invariant firm-specific characteristics, we reestimated the regressions of model (1) using the firm fixed effects model, when TFP is adopted as the dependent variable. The regression results of the fixed effects model are shown in Panel A of Table 5. In Column (2), the coefficient of ESG is 0.008 at the 1% significance level. It implies that our results are not driven by any time-invariant firm-specific characteristic, and the results are robust for endogeneity issues.

Propensity score matching procedure

Propensity score matching (PSM) procedure was used to reduce the influence of sample firms' characteristics on conclusions. The firm size (Size), return on assets (ROA), leverage (Lev), growth opportunity (Growth), firm age (FirmAge), year, and industry were matched one to one. The mean ESG performance was taken as the critical value to construct the experimental group and the control group. After the ESG was matched and from Column (3) of Panel A of Table 5, the estimated coefficient of ESG is still positive and significant at the 1% significance level, which does not change the original conclusion.

Instrumental variables approach

Next, we used the method of instrumental variables to solve the endogeneity problem. We attempted to construct a group of instrumental variables (IV). In the previous literature, the ESG level at the industry or region level was used as the instrumental variable (IV) of ESG of the firm (Breuer et al., 2018).

To solve the endogeneity issue further, we chose the average value of ESG in the same region or industry as the instrumental variable. From Panel B of Table 5, Column (1) shows that the coefficient of IV is 0.866 at the 1% significance level. It indicates that the IV we selected is highly correlated with ESG. The results of Column (2) showed that the coefficient of IV is 0.039 at the 1% significance level. It indicates that, after controlling for the endogeneity

TABLE 6 Robustness tests.

	<i>TFP_op</i> (1)	<i>TFP_lp</i> (2)
<i>ESG</i>	0.096*** (20.326)	
<i>ESG_dum</i>		0.020** (2.251)
<i>Size</i>	0.408*** (88.385)	0.647*** (144.423)
<i>ROA</i>	2.645*** (30.401)	1.914*** (27.246)
<i>Lev</i>	1.738*** (57.904)	0.816*** (30.278)
<i>Growth</i>	0.143*** (11.027)	0.123*** (11.783)
<i>Cashflow</i>	0.420*** (5.023)	0.704*** (10.502)
<i>FirmAge</i>	−0.002 (−0.110)	0.011 (0.796)
<i>Indep</i>	−0.076 (−0.818)	−0.320*** (−4.326)
<i>Dual</i>	−0.073*** (−6.593)	−0.037*** (−4.176)
<i>Top1</i>	0.230*** (6.366)	0.201*** (6.947)
<i>SOE</i>	0.187*** (13.906)	0.059*** (5.438)
<i>Constant</i>	12.284*** (120.980)	1.077*** (9.018)
<i>Year</i>	Yes	Yes
<i>Indu</i>	Yes	Yes
<i>N</i>	15,748	15,755
<i>r2</i>	0.501	0.801

The t-statistics reported in parentheses are based on standard errors clustered at the firm level. ***, **, and * denote significance at the 1, 5, and 10% levels, respectively.

problems of ESG, the conclusion of the present study still holds.

Other robustness checks

Alternative methods of identifying independent variables

We confirm the robustness of our results by two alternative approaches. First, the alternative methods of identifying independent variables for ESG are used. Following (Lin et al., 2021), the proportional variable (*ESG_dum*) is used as a new identifying method for ESG. Column (2) of Table 6 shows that

the coefficient of *ESG_dum* is still significantly positive at the level of 1%. After changing the independent variable identifying method, we find that ESG increases TFP significantly.

Alternative methods of identifying dependent variables

From Column (2) of Table 6, the new regression analysis results of changing the dependent variable TFP calculation method are obtained. Following Olley and Pakes (1996), we recalculated the TFP. The regression analysis results prove that the results of the above mentioned basic regression analysis are robust.

Conclusion

The present study details various factors as to whether and how ESG affects TFP. Using the data of Chinese-listed companies from 2010 to 2020, it has been proved that ESG has a significantly positive impact on TFP. Through the mediating effect analysis, we found that the positive impact of ESG on TFP is mainly brought about by promoting technological innovation and easing financial constraints, which are consistent with previous studies. At the same time, we also found that ESG has a more significant impact on TFP for state-owned enterprises (SOEs) and heavy pollution enterprises. The robustness test also further supports our conclusion.

Our research emphasizes the importance of ESG to the TFP of enterprises and shows that increasing the R&D investment of listed companies in ESG is conducive to promoting the sustainable growth and development of enterprises. Based on our research, we propose the following three suggestions. First, enterprises should promote the implementation of ESG responsibilities as a strategy to drive the long-term value of enterprises. We should further strengthened the awareness of ESG responsibility and placed the improvement of environmental protection, social responsibilities, and corporate governance in an important position to promote the sustainable development of enterprises. Second, the government should improve the mechanism of evaluation and information disclosure for an enterprise's ESG, provide effective data to support the decision-making of stakeholders, and further promote the high-quality development of economy and enterprises. Third, in the context of sustainable development, institutional investors and individual investors, who are outside the enterprise, should not only pay attention to the financial performance of the enterprise but also focus on the ESG performance of the enterprise in the process of investment so as to obtain greater benefits.

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

JM and DG contributed to the conception, design of the study, and performed the statistical analysis. DG and JS organized the database. JM, DG, and JS wrote the draft of the manuscript and contributed to writing–review and editing. All authors contributed to manuscript revision, read, and approved the submitted version.

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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/fevo.2022.1063736/full#supplementary-material>

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Appendix

TABLE A1 Variable definitions.

Variable	Definition
<i>TFP</i>	Total factor productivity measured by the LP method (Levinsohn and Petrin, 2003), defined as the (log) level of TFP of firm <i>i</i> at year <i>t</i> .
<i>TFP_{op}</i>	TFP is measured using Olley and Pakes (1996) non-parametric method.
<i>ESG</i>	ESG index developed by Sino-Securities Index Information Service (Shanghai) Co. Ltd. for all listed firms in China, following Lin et al. (2021).
<i>Size</i>	The natural logarithm of total assets
<i>ROA</i>	The company's net profit divided by the total assets
<i>Lev</i>	The value of liabilities divided by total assets
<i>Grow</i>	The annual growth rate of sales
<i>Cash</i>	The sum of cash scaled by total assets
<i>FirmAge</i>	The log value of firms' age.
<i>Indep</i>	The total number of shares traded in a year, divided by the total number of shares outstanding at the end of the fiscal year
<i>Dual</i>	1 if the CEO is also the chairman of the board, and 0 otherwise.
<i>Top1</i>	The first largest shareholder equity ratio
<i>SOE</i>	1 if the firm is a state-owned firm, and 0 otherwise
<i>RD</i>	R&D intensity, which is measured by the ratio of R&D investment to operating income
<i>KZ</i>	Financing Constraints index of firm <i>i</i> at year <i>t</i> , following Kaplan and Zingales (1997).



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Whether it is economical to use combined heat and power (CHP) system for the efficient utilization of associated petroleum gas in oil extraction sites in China: A cost-benefit analysis considering environmental benefits

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The efficient use of associated petroleum gas with combined heat and power (CHP) systems in oil extraction sites has proven to be technically feasible, but its economic inefficiency continues to deter oil companies from using CHP, given that simple fuel cost reductions do not yield significant positive returns in the face of large investments in purchasing and maintaining CHP. This research constructs a cost-benefit analysis model, which includes the monetized environmental benefits generated by CHP. A pilot experiment operated in a certain oilfield in Shandong province shows that the annual difference between the reduction in fuel costs and the investment in purchase and maintenance of CHP is only about ¥210,000 per device. However, when environmental benefits including health benefit and low-carbon benefit are included in the model, the annual environmental benefits of a single equipment update can be about ¥760,000, and the overall annual net benefits will reach about ¥970,000. It is concluded that the application of CHP in oil extraction sites is economically efficient, taking into account the environmental benefit it can produce. The research results will help oil companies use CHP to make more contributions to carbon and air pollutant emission reduction. However, considering that a large number of CHP systems can form a distributed energy structure, the proposed model still has limitations.

KEYWORDS

cost-benefit analysis, associated petroleum gas, combined heat and power (CHP) system, environmental benefit, health benefit, low-carbon benefit

1 Introduction

Oil extraction sites in oilfields are ideal scenarios for applying combined heat and power (CHP) systems. It is because a) Oil extraction sites have both electricity and heat needs. There is a large amount of electrical equipment at the site, and the temperature of the freshly extracted crude oil once it enters the site needs to be maintained at around 70°C for subsequent transportation (Osintsev et al., 2019); b) CHP can use associated petroleum gas as fuel, which reduces the cost of fuel. Previously, oil extraction sites burned associated petroleum gas directly into the atmosphere through torches (Rajović et al., 2016); c) The use of CHP can reduce the emission of carbon dioxide, nitrogen oxide, and PM2.5 (Shi et al., 2022). It is because the source of electricity has changed from a coal-fired thermal power plant to CHP fueled by associated petroleum gas (Ekaterina et al., 2017; Zhu et al., 2019), meanwhile the source of heat has changed from the original heating equipment to CHP with a higher process level (Berg et al., 2019). However, previous studies have only focused on discussing whether it is technically feasible to use CHP to achieve efficient use of associated petroleum gas, neglecting whether the scheme is economical.

Regarding the application of CHP in other application scenarios (e.g. school, shopping mall, and office building), previous studies have shown that considering the high cost of purchasing and maintaining CHP, making them economical requires stringent conditions, including low operating power and low fuel prices (Ghorbani et al., 2016; Amber et al., 2018; Yang et al., 2019; Hossein et al., 2021). Although oil extraction sites can use low-cost associated petroleum gas as fuel for CHP, it is still difficult to offset the investment cost by reducing fuel costs alone, leaving oil companies unable to operate CHP at normal power levels to fully meet the sites' thermal and electrical needs. In short, if only fuel cost reduction and investment in purchase and maintenance of CHP are included in the cost-benefit calculation, it is difficult for CHP to be economical at normal power.

Previous studies have demonstrated that CHP is eco-friendly (Maurovich-Horvat et al., 2016; Perea et al., 2016; Cora et al., 2019). At the same time, China's "Dual Carbon" goals put forward higher requirements for enterprises' contribution to carbon emission reduction (Guo et al., 2022). Therefore, the environmental benefits of CHP cannot be ignored. This research monetizes the environmental benefit arising from the use of CHP and incorporates it into the cost-benefit analysis model. Through this model, this research analyzes whether the use of CHP in oil extraction sites can be economically operated at the required operating power in the face of high investment in purchase and maintenance of CHP, considering its environmental benefits and fuel cost reduction. To prove that the total benefits of using CHP are significantly higher than the investment in purchase and maintenance of CHP, a pilot experiment from an oilfield in Shandong Province is used as a case study.

This article is organized as follows: theoretical models to quantify the benefits and costs of applying CHP are presented in Section 2; empirical results are presented in Section 3; the conclusion proved by empirical findings and discussions on potential extensions and limitations of the theoretical models are presented in Section 4.

2 Theoretical models

A model for quantitative analysis of the economic benefits of using CHP is expressed as follows:

$$E_{entire} = \sum_{i=1}^n E_{health_i} + E_{lowcarbon_i} + E_{fuelcost_i} - C_{site_i}$$

where E_{entire} is the entire economic benefit of replacing the existing supply program of electricity and heat with CHP at oil extraction sites. E_{health_i} is the health benefit due to reduced emissions of air pollutants, considering that fewer people will become ill or die from air pollutants; $E_{lowcarbon_i}$ is the low-carbon benefit due to the reduction of greenhouse gas emissions; $E_{fuelcost_i}$ is the cost reduction value caused by the use of associated petroleum gas as fuel in CHP; C_{site_i} is the investment in purchase and maintenance of CHP. Different subscripts of variables mean different periods reflected by the data, considering that the demand for heat will vary greatly with seasonal changes, it would be more accurate to use monthly or quarterly data. When analyzing, annual operation-related data from the target equipment and data from publicly available databases (e.g. Statistical Yearbooks of governments, National Health Commission) should be obtained.

2.1 Monetary quantification of health benefit

Switching from coal-fired power plants to CHP that burns associated petroleum gas has resulted in lower PM2.5 emissions and lower rates of respiratory and cardiovascular disease caused by an excessive level of PM2.5 in the air, resulting in health benefit. According to the environmental health value assessment theory (Huang et al., 2013; Du et al., 2021a), the following model is built:

$$E_{health_i} = Risk_{in} * C_{in}$$

where $Risk_{in}$ is the health risk change of the health effect endpoint n , which needs to be calculated by the environmental health risk assessment method (Jung et al., 2010; Faisya et al., 2018; Putri et al., 2019; Sandra et al., 2021; Thu et al., 2021); C_{in} is the value corresponding to the change in health risk per unit of health effect endpoint n , which needs to be obtained through an environmental health value assessment method (Gentry et al., 2016; Mori et al., 2019; Kim et al., 2022).

The change in health risk is based on the epidemiological “exposure-response relationship” and combined with the relative risk model using Poisson regression. Thus, the following formula is constructed:

$$\begin{aligned} Risk_{in1} &= Risk_{in0} \times \exp(\beta \times q_{ci}) \\ Risk_{in} &= P_i \times (Risk_{in1} - Risk_{in0}) \end{aligned}$$

where P_i is the number of exposed population; q_{ci} is the change in PM2.5 concentration after the power supply and heating methods of the pilot experimental site are changed; $Risk_{in1}$ and $Risk_{in0}$ are the health conditions under two concentration levels of PM2.5 (c and c_0), respectively. This research uses $Risk_{in1}$ calculated by Du (Du et al., 2021b); β is the exposure-response relationship coefficient. Previous researchers have analyzed and proposed the exposure-response relationship coefficient applicable to different regions of China (Kan et al., 2004; Xie et al., 2009; Lu et al., 2016).

For the economic loss caused by the premature death of residents caused by PM2.5, this research adopts the Value of a Statistical Life Method (VSL) to evaluate. Xie's method based on the choice experiment estimated the VSL of Beijing residents in 2010 (Xie, 2011). It is denoted as VSL_{io} and the following formula is constructed:

$$VSL_{i1} = VSL_{io} \times (Income_{i1} \div Income_{io}) \times elasticity$$

by adjusting VSL_{io} , we can get the latest VSL_{i1} of the residents in the oilfield. Furthermore, $Income_{i1}$ represents the *per capita* disposable income of the oilfield area; $Income_{io}$ is the *per capita* disposable income of Beijing (Beijing Municipal Bureau of Statistics, 2010); elasticity is the income elasticity of residents.

For outpatient and inpatient expenses, this research uses the cost of disease method to estimate the formula as follows:

$$C_{in} = C_{pi} + GDP_i \times T_{in}$$

where C_{in} is the total cost of disease caused by PM2.5 to health effect endpoint i ; C_{pi} is the medical expense per unit case of health effect endpoint i ; GDP_i is the daily average of *per capita* gross national product in oilfields; T_{in} is the time lost due to illness for health effect endpoint i . The selected health effect endpoints affected by PM2.5 in this research are premature death, hospitalization for respiratory diseases, hospitalization for cardiovascular diseases, medical outpatient clinics, pediatric outpatient clinics, acute bronchitis, chronic bronchitis, and asthma (Du et al., 2021a). Among them, the disease cost method is not suitable for chronic bronchitis due to the difficulty in determining the duration of the disease. This research refers to the result of Viscusi, which is set to be 32% of VSL (Viscusi et al., 1991).

2.2 Monetary quantification of low-carbon benefit

Using CHP to generate electricity, the power generation energy is changed from coal to associated petroleum gas, and

carbon dioxide emissions are reduced, hence low-carbon benefit is generated (Maurovich-Horvat et al., 2016; Cora et al., 2019).

The product of reduced greenhouse gas emissions and carbon trading price is used as the monetized low-carbon benefit. It is calculated as follows:

$$Elowcarbon_i = (R_i + R'_i) \times P$$

where R_i represents the CO₂ emission reduction caused by changing the power supply source of the pilot experimental site; R'_i represents the NO_x emission reduction caused by changing the heating source of the pilot experimental site; P is the carbon trading price.

The formula for calculating CO₂ emission reduction in the pilot experiment is as follows:

$$R_i = e_{i1} \times Q_{i1} - e_{i2} \times Q_{i2}$$

where R_i represents the CO₂ emission reduction caused by changing the power supply source of the pilot experimental site; e_{i1} is the power carbon emission coefficient of CO₂ during coal-fired power generation; Q_{i1} is the power supply; e_{i2} is the carbon emission coefficient of CO₂ when the associated petroleum gas is burned after the use of CHP; Q_{i2} is the total amount of natural gas consumed.

The critical emission temperature of nitrogen oxides is 1,400 °C, and the higher the temperature, the more nitrogen oxides will be produced. While the original heating equipment burns at temperatures above 1,400 °C, CHP uses low-temperature combustion technology. It can control the combustion temperature at around 1,300°C (Yao et al., 2022). Therefore, compared with the original heating equipment, CHP reduces the emission of nitrogen oxides and produces low-carbon benefit. The formula for calculating NO_x emission reduction is as follows:

$$R'_i = (v_{i1} \times T_{i1} - v_{i2} \times T_{i2}) \times GWP$$

where R'_i represents the NO_x emission reduction caused by changing the heating source of the pilot experimental site; v_{i1} represents the NO_x emission rate when the original heating equipment continues to produce heat; T_{i1} represents the annual operating time of the original heating equipment; v_{i2} represents the NO_x emission rate when using CHP; T_{i2} represents the annual operating time of CHP; GWP represents the global warming potential value of NO_x, which is used to convert NO_x into the corresponding CO₂ Emissions.

2.3 Cost reduction due to the use of oil associated petroleum gas

The emission standards of air pollutants in various regions of China are becoming increasingly strict. Considering that the new pollutant emission standards have been implemented, even oil

companies have not opted for the plan to introduce CHP (i.e. the “renewal plan”), it is also necessary for oil companies to apply the plan that using low nitrogen burner and flue gas treatment equipment to meet emission standards (i.e. the “improvement plan”). Therefore, the formula for calculating the cost reduction is as follows:

$$E_{fuelcost_i} = P_{extra_i} + V_{i2} \times P_{i2} + V_{i3} \times P_{i3} - V_{i1} \times P_{i1}$$

where $E_{fuelcost_i}$ represents the value of cost reduction for the renewal plan compared with the improvement plan; P_{extra_i} represents the cost of installing low-nitrogen burners and flue gas treatment equipment for the original heating equipment; V_{i1} represents the total amount of associated petroleum gas required under the renewal plan; P_{i1} represents the cost of using associated petroleum gas; V_{i2} represents the total amount of electricity purchased under the improvement plan; P_{i2} represents the purchase price of electricity; V_{i3} represents the total amount of natural gas of original quality required under the improvement plan; P_{i3} represents the purchase price of natural gas of original quality.

2.4 Investment in purchase and maintenance of CHP

The initial investment cost of CHP is higher than that of existing heating equipment. At the same time, the operation stability of CHP is less than that of the existing heating equipment, the maintenance cost of its operation is also higher than that of the existing heating equipment. Therefore, this research analyzes the increased investment cost of energy supply plan renewal from two directions: equipment investment cost and operation cost:

$$C_{site_i} = EIC_{intire_i} + EOMC_{intire_i}$$

where EIC_{intire_i} represents the difference between the annual discounted value of the equipment investment cost; $EOMC_{intire_i}$ represents the difference between equipment operation and maintenance costs.

Given that most of the equipment investment cost is a one-time investment at the beginning of the period, this research uses the following formula to amortize the equipment investment cost for each year according to the service life of the project or equipment and the social discount rate:

$$EIC = \frac{IIC \times R \times (1 + R)^T}{(1 + R)^{T-1}}$$

where EIC represents the annual discounted value of the equipment investment cost, R is the social discount rate, and T is the service life of the equipment. IIC is the one-time initial investment cost of purchasing equipment. Hence:

$$EIC_{intire_i} = EIC_{i1} - EIC_{i2}$$

where EIC_{i1} represents the sum of the annual discounted value of the equipment investment cost of CHP, and EIC_{i2} represents the sum of equipment investment of the original heating equipment's annual discounted value of cost.

$$EOMC_{intire_i} = EOMC_{i1} - EOMC_{i2}$$

where $EOMC_{i1}$ represents the sum of operation and maintenance costs of CHP, and $EOMC_{i2}$ represents the sum of operation and maintenance costs of the original heating equipment.

3 Case analysis

Since 2021, a pilot experiment about CHP has been conducted at an oil extraction site in an oilfield in Shandong province. The pilot experiment continued for more than a year until mid-2022. After obtaining 1-year data from the pilot experiment and other publicly available data, this research introduced the data into the model constructed in Section 2 and obtained the following results.

To operate CHP continuously for 1 year at an oil extraction site to replace the previous heat and electricity supply system requires an investment of about ¥560,000 in purchase and maintenance. Correspondingly, CHP can generate about ¥730,000 in health benefit, about ¥30,000 in low-carbon benefit, and about ¥770,000 in fuel cost reductions over a year (Table 1).

Table 2 shows the details of the health benefit.

In the face of high investment in purchase and maintenance of CHP, if only the fuel cost reduction is counted as the benefit, the application of CHP can only generate a net benefit of ¥210,000, that is, a net interest rate of 27.3%. However, if the environmental benefits produced by CHP are taken into account in the cost-benefit analysis, the overall net benefit can reach ¥970,000, with a net interest rate of 63.4% (Figure 1).

In conclusion, the pilot experiment in an oilfield in Shandong Province has demonstrated that it is economical to replace the previous heat and electricity supply system with CHP at an oil extraction site after incorporating environmental benefits into the cost-benefit analysis.

4 Discussion

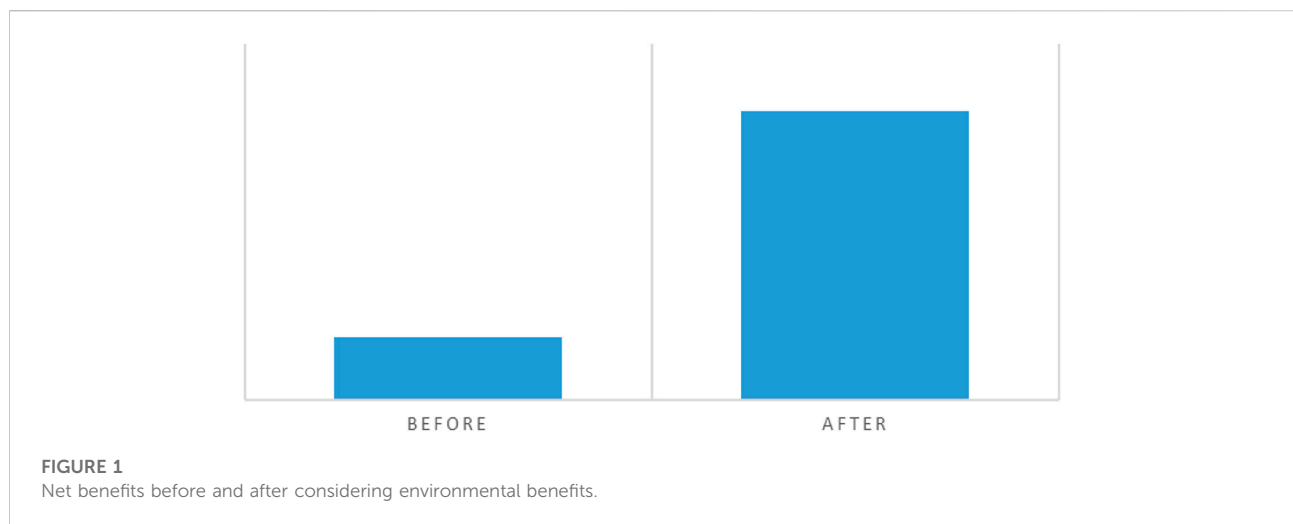
Previous studies on the prospect of combined heat and power for public use have shown that the high investment in purchase and maintenance of combined heat and power causes stringent conditions to make it economical, including low operating power and low fuel price. Although low fuel price can be achieved by using associated petroleum gas as fuel for oil extraction sites, keeping combined heat and power operating at low power is not

TABLE 1 Summarized benefits of applying CHP.

Category	Benefit (yuan)
Health Benefit	732,875.21
Low-carbon Benefit	29,032.59
Cost Reduction due to the Use of Oil Associated Petroleum Gas	767,461.21
Investment in Purchase and Maintenance of CHP	-556,853.20

TABLE 2 Monetary quantification of health benefit.

Disease	Health effect endpoint	Health benefit (yuan)
Premature Death	Premature Death	300,162.00
Hospitalization	Respiratory Diseases	1,476.41
	Cardiovascular Diseases	477.66
Outpatient Service	Pediatrics	173.57
	Internal Medicine	458.75
Other Illnesses	Acute Bronchitis	16,771.45
	Chronic Bronchitis	410,541.00
	Asthma	2,814.37
Total		732,875.21



acceptable for oil extraction sites. Therefore, if combined heat and power is operating at normal power at oil extraction sites, oil companies are concerned about whether the simple reduction in fuel cost can make the use of combined heat and power profitable.

This research provides a model that includes monetized health and low-carbon benefits, cost reduction value, and

investment in purchase and maintenance of combined heat and power. In [Sections 2.1, 2.2](#), this research provides the idea of monetizing the economic benefits generated by combined heat and power. Using data on reductions in the number of respiratory and cardiovascular diseases and deaths among residents, this research calculates the economic benefits of

reducing air pollutants (i.e. health benefit). At the same time, from the perspective that oil companies can make profits in the carbon trading market through greenhouse gas emission reduction, this research calculates the economic benefits generated by greenhouse gas emission reduction (i.e. low-carbon benefit). The calculation methods of fuel cost reduction and investment in purchase and maintenance of combined heat and power are presented in Sections 2.3, 2.4, respectively.

The model in this research helps oil companies verify whether the following conclusion holds in a specific oilfield area: When applying combined heat and power to oil extraction sites, if environmental benefits are taken into account in the cost-benefit analysis, combined heat and power can be economical at normal power operating conditions. To verify the feasibility of the model, a pilot experiment of combined heat and power in an oilfield in Shandong Province is used as a case, which successfully proves that the above conclusion is valid in the oilfield in Shandong Province. In sum, the model in this research can guide oil companies when analyzing whether to use combined heat and power in an oilfield. While promoting the reduction of air pollutant emission, the use of combined heat and power as a thermal and power supply solution for oil extraction sites will also help oil companies slow down global warming in terms of deep decarbonization to meet the 1.5°C–2°C target. Moreover, with the expansion of urbanized areas, more oil field facilities that emit pollutants that were originally far away from urban residential areas will directly affect the surrounding residents. In this case, the application of combined heat and power will not only make the oil field facilities that emit pollutants directly profit from the equipment renewal, but also alleviate the tension between them and the surrounding residents due to the emission of pollutants.

This research's model still has limitations. Considering the wide distribution and a large number of oil extraction sites in the entire oilfield area, if the number of sites using combined heat and power is large enough, the economy of scale will be formed (Carvajal et al., 2019), which makes the model in this research need to be revised. Moreover, when the site's heat and power needs are met, there is still a lot of associated petroleum gas left over (Valentin et al., 2020). The ability to integrate combined heat and power at different sites into the same power network, which could provide power not only for the site itself but also for

other industrial and even civil facilities nearby (Stoltmann et al., 2019), would also generate additional benefits. Finally, the power network composed of a large number of combined heat and power belongs to a distributed energy structure. Compared with the power network from a single source, the power network with distributed energy structure has a stronger anti-risk ability in the face of power failure (Zeng et al., 2020; Chin et al., 2021; Marcos et al., 2022). The corresponding benefits will also be generated as the number of unexpected production interruptions due to power outages decreases (Kayoung Kim et al., 2017; Karyn Morrissey et al., 2018; Tensay Hadush Meles et al., 2021). For oil companies that want to use combined heat and power on a wider scale, the model needs to be revised.

Data availability statement

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

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

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 the National Specially Monitored Firms program improve corporate environmental performance?—Empirical evidence from China

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As an important measure of reform of the central environmental supervision, the National Specially Monitored Firms program has a significant impact on enterprise pollution control. However, there are few studies that have systematically studied the mechanism of this system on enterprise environmental performance. Based on the quasi natural experiment of the National Specially Monitored Firms program, this article uses the emission data of industrial enterprises from 2001 to 2009 to investigate the impact of the central environmental supervision on corporate environmental performance by using the DID method. It is found that the National Specially Monitored Firms program has significantly improved the corporate environmental performance of the monitored enterprises. Heterogeneity analysis finds that when compared with enterprises with a higher degree of financing constraints, export enterprises, and enterprises with a lower level of economic development in the region, the implementation of the National Specially Monitored Firms program has a more significant effect on improving the environmental performance of enterprises with a lower degree of financing constraints, domestic enterprises, and enterprises with a higher level of economic development in the region. The mechanism test shows that improving the enterprise environmental protection equipment investment is not the only intermediary mechanism for the National Specially Monitored Firms program to improve corporate environmental performance. The conclusions of this article are not only conducive in optimizing the environmental governance methods but also inspirational for monitoring practices in other fields.

KEYWORDS

National Specially Monitored Firms program, corporate environmental performance, financing constraints, export enterprises, level of economic development

1 Introduction

In recent years, with the rapid development of the economy, problems such as environmental pollution, ecological damage, and excessive consumption of resources have become very serious (Su and An, 2018; Tao et al., 2022) will all limit the sustainable development of the world economy (Muller et al., 2011; Gupta et al., 2019). To this end, governments are actively building a sound environmental legal system. Although remarkable results have been achieved, some pollution problems are still continuing. In particular, as an important participant in the market economy and a major emitter of pollutants, enterprises are pursuing economic goals. In the process, the environmental problems highlighted above are becoming increasingly serious. For example, the “A-share ESG rating analysis report 2020” shows that from June 2012 to June 2020, there were 19,770 ESG risk events in China, which included 8,447 environmental risk events, accounting for 43%, ranking first. It can be seen that enterprises have become heavy disaster areas of current environmental pollution.

The existing research on the driving factors of corporate environmental performance mainly involves the environmental system, market competition, and internal governance (Tran and Pham, 2020; Chen et al., 2021; Zhou et al., 2021; Wang et al., 2022), where environmental regimes are a core driver of corporate environmental performance. At present, the number of environmental laws, regulations, and normative documents in China has been the same as that in developed countries, but the enforcement of the local environmental law is poor (Lu, 2022). This is because, as a formal system, the operation process of the policy includes two links: formulation and implementation. The governance effect of the final policy depends 90% on the implementation link (Shen and Zhou, 2017). Policy implementation is the key factor in determining whether the policy is effective. This is especially true for environmental policies. Especially under China’s current environmental decentralization system, the implementation process of environmental policies is formed by a set of complex principal–agent chains, and there must be different principal–agent problems between the different levels (Yu, 2016). First, at the level of the central government and local government, the central government is the principal and the local government is the agent. The relationship between the two is “decision-making and implementation,” and the target difference, information gap, and limited regulatory capacity between the two will lead to poor environmental law enforcement by the local governments (Khanna and Anton, 2002; Zhang et al., 2019), resulting in the principal–agent problem. Second, at the level of the local governments and enterprises, the local governments are principals and enterprises are agents, and the relationship between them is “to regulate and be regulated, to support and be supported”; however, information asymmetry between the government and

enterprises, high difficulty of environmental evaluation, and limited monitoring and inspection capabilities of the local regulators (Van Rooij, 2006) all lead enterprises to send false environmental information to government departments, resulting in adverse selection problems. In addition, local governments have greater law enforcement discretion over China’s administrative, economic, and social resources, creating rent-seeking opportunities for enterprises (Du and Mickiewicz, 2016), especially in resource-poor areas where moral hazards are more likely to occur. Third, at the level of people and government, people and enterprises, people are the principal and the government and enterprises are the agents. The relationship between them is “supervision and supervised.” When compared with the government and enterprises, people lack the necessary information sources, and the low threshold conditions in obtaining information lead to the inability of implementing the environmental policy chain in forming effective policy closed loops in the feedback links. If the principal–agent problem at different levels cannot be solved comprehensively, the effect of the environmental policy is greatly reduced.

To strengthen the supervision of implementation of the environmental policies, the central government has introduced a series of environmental supervision measures, such as auditing the departure of natural resource assets of leading cadres, environmental supervision, environmental interviews, and government environmental audits (Earnhart et al., 2020; Wu et al., 2020; Cao et al., 2021; Wang et al., 2021; Jiang et al., 2022). In 2007, China fully established the National Specially Monitored Firms program (hereinafter referred to as the “NSMF program”), which aims to reform China’s traditional environmental decentralization system (Zhang et al., 2018). Different from the other means of environmental supervision, the NSMF program has unique advantages, mainly in the following: first, the “supervise local governments” feature deters local governments’ environmental law enforcement efforts. Second, the characteristics of “regulated enterprises” regulate the illegal discharge of enterprises. Third, the threshold of public participation is lowered, and the supervision of local governments and enterprises is strengthened. It can be seen that the NSMF program aims at the complex principal–agent chain in the process of environmental governance and constructs an environmental governance system led by the government, with enterprises as the main body and social organizations and the public participating together, which effectively makes up for the shortcomings of other environmental regulatory measures. Scholars have conducted much discussion on the NSMF program, but mainly, there is a lack of empirical research around the policy itself, especially at the microlevel. However, how microenterprises respond to the policy is very important to test the environmental governance effect of the NSMF program. Therefore, this article proposes the following questions: can the NSMF program effectively improve corporate environmental

performance? Will it effectively show the heterogeneity of enterprises?

When compared with existing literature, we have made several contributions to the literature mainly in three aspects. First, this article expands the research paradigm of the NSMF program. The literature mainly discusses the policy requirements, technology application, and improvement methods of state-controlled projects from the theoretical level. Few scholars use empirical data to study the impact of the NSMF program on microenterprises, which makes the operation and implementation of the NSMF program lack practical microlevel theoretical support and guidance. This article uses empirical methods to explore the impact of the NSMF program on corporate environmental performance and expands the research paradigm of the NSMF program from normative to empirical, which is a good supplement to this research field. Second, this article enriches the influencing factors of corporate environmental performance. At present, a few scholars have discussed the impact of environmental policies on corporate environmental performance. However, on the one hand, the literature only examines the impact of environmental policies on corporate environmental behavior from a single perspective of “supervise local governments” environmental policies or “regulated enterprises” environmental policies, which inevitably separate the entire principal–agent chain in the process of environmental governance and cannot accurately evaluate the implementation effect of environmental policies. On the other hand, when discussing the micro-effects of environmental policies, the literature has not comprehensively analyzed the principal–agent problems between different levels and lacks a complete and systematic analysis framework. This article starts from an environmental policy with the characteristics of both “supervise local governments” and “regulated enterprises,” integrates various principal–agent problems in the implementation chain of the environmental policy, examines the impact of the NSMF program on corporate environmental performance, and enriches the literature in this field. Third, this article identifies the mechanism of the NSMF program on corporate environmental performance. The implementation effect of the environmental policies is usually related to the implementation efficiency of the local governments. With the frequent occurrence of corporate pollution problems in China, exploring the impact of environmental law enforcement supervision on corporate environmental performance has practical significance. This article not only discusses the impact mechanism of the NSMF program on corporate environmental performance but also conducts in-depth research based on different situations, which provides directional guidance and policy reference for better playing the role of the NSMF program in environmental governance.

The rest of this article is organized as follows: [Section 2](#) reviews previous relevant studies, [Section 3](#) proposes research assumptions, [Section 4](#) describes the data and variables, [Section 5](#)

reports the empirical results, and [Section 6](#) summarizes the findings and provides policy implications.

2 Literature review

2.1 National Specially Monitored Firms program

As an important part of the central environmental supervision, the NSMF program is an environmental regulation that introduces modern means for environmental governance. Specifically, first, the NSMF program determines whether it is included in the national control list according to the pollution emissions of the enterprise in the past two years; subsequently, enterprises included in the national control list must install and maintain automatic monitoring equipment for pollution sources according to regulations and transmit real-time emission data to the national monitoring network; and finally, the monitoring center supervises and inspects the data on a monthly basis and requires at least one on-site inspection per month to ensure the normal operation of the pollution source automatic monitoring equipment and accuracy of the data. The existing research on the NSMF program is still relatively scarce, mainly focusing on the following four aspects. First, there is research on the program itself. For example, [Yuan and Cao \(2017\)](#) analyzed the existing problems of the NSMF program and proposed corresponding countermeasures and suggestions. Second, there is research on the application of project monitoring data. For example, [Gao et al. \(2020\)](#) analyzed the problems in the use of monitoring data for sewage treatment. Third, there is research on the key monitoring enterprises of the NSMF program. For example, [Yin et al. \(2018\)](#) proposed the “disciplinary cage” hypothesis by taking the key monitoring enterprises of the NSMF program, while [Yin et al. \(2020\)](#) took the key monitoring enterprises of the NSMF program as the research object and found that the replacement of municipal party secretaries negatively affected enterprise innovation; fourth, they researched the implementation consequences of the NSMF program. For example, [Fang et al. \(2020\)](#) used empirical evidence from the NSMF program and enterprise-level data from 2001 to 2009 to study the impact of environmental regulation on enterprise innovation. They found that the implementation of the NSMF program has increased the innovation of monitored enterprises and verified the weak Porter hypothesis theory.

2.2 Corporate environmental performance

Enterprises are important “consumers” of natural resources and major emitters of pollutants, and the improvement in their

environmental performance is the micro-foundation for achieving environmental governance objectives. In fact, corporate environmental performance has immeasurable value for the long-term development of enterprises and high-quality development of the national economy. For enterprises, the improvement in corporate environmental performance can promote technological innovation, improve production efficiency, enhance social reputation, attract environmentally sensitive customers, and increase corporate competitive advantages (Hart and Ahuja, 1996; Konar and Cohen, 2001; Orlitzky et al., 2003) to promote the sustainable development of enterprises. Therefore, how to improve corporate environmental performance has become an important issue for the government, society, and enterprises.

At present, a large number of scholars have explored the influencing factors of corporate environmental performance. First, at the microlevel, some scholars believe that executive compensation (Zou et al., 2015), executive characteristics (Francoeur et al., 2020; Tran and Pham, 2020), and internal carbon pricing (Zhu et al., 2022) will have an impact on corporate environmental performance. Second, at the meso level, they mainly examine the impact of community pressure (Zhou et al., 2021), social trust (Chen et al., 2021), and stock market value (Endo, 2019) on corporate environmental performance. Third, at the macro-level, this article is directly related to the environmental policy and corporate environmental performance literature. For example, Earnhart et al. (2020) empirically analyzed the impact of law enforcement fairness on corporate environmental performance, indicating that unfair law enforcement methods will enable companies to show better environmental performance levels. Jiang et al. (2022) investigated the impact of the natural resource asset departure audit policy on corporate environmental performance and concluded that the departure audit significantly promoted the improvement of corporate environmental performance. Cao et al. (2021) examined the impact of government audits on corporate environmental performance, taking the vertical management reform initiative of government audit institutions piloted in China in 2015 as an example, and believed that government audits can improve corporate environmental performance. Wang et al. (2022) investigated the impact of central environmental protection inspectors on corporate environmental investment and concluded that central environmental protection inspectors effectively increased the level of corporate environmental investment.

3 Hypothesis development

3.1 National Specially Monitored Firms program and corporate environmental performance

Since 2006, China has gradually shifted the main body of responsibility for pollution control and environmental protection

supervision from enterprises to the local government. However, while the “supervise local government” environmental policy has achieved certain results, it has also caused a series of problems worthy of attention. For example, some local governments use environmental data manipulation to modify environmental assessment indicators (Chen et al., 2012). The NSMF program introduces informatization and modernization for environmental governance, optimizes the information communication path between various levels in the environmental decentralization system, and improves the existing environmental law enforcement problems in China. This article believes that the NSMF program mainly affects the environmental performance of enterprises from the following three aspects. First, the NSMF program can alleviate the principal-agent problem between the central government and local governments and improve corporate environmental performance by deterring the local governments’ environmental enforcement efforts. Under a decentralized system with Chinese characteristics, the vast majority of law enforcement power is delegated to local governments (Li et al., 2020), and the “GDP tournament” makes local governments often acquiesce with companies “abandoning the environment and protecting the economy” when acting as agents, leading to the failure of the local government’s control of pollution (Sun et al., 2021). The NSMF program introduces advanced technologies such as informatization and automation into environmental law enforcement and has the advantages of continuous online, all-day operation, and nationwide networking such that the central government can directly collect more reliable and accurate information on enterprise pollution emissions, enable local governments to accept law enforcement supervision in a more transparent environment, and form a deterrent to local governments. At this point, the local government passes the supervision pressure from the central government on environmental protection law enforcement to the local enterprises and strengthens environmental supervision or assessment (Jiang et al., 2022). Under the pressure of environmental protection, enterprises must take measures such as factory shutdown, production reduction, and green innovation to reduce emissions (Zhao et al., 2015; Hashmi and Alam, 2019; Fang et al., 2020; Yang et al., 2020) to improve environmental performance.

Second, the NSMF program can alleviate the principal-agent problem between local governments and enterprises and regulate the illegal discharge of enterprises by improving the environmental law enforcement level of local governments. Under the traditional environmental supervision mode, it is difficult for local governments to grasp the real pollution level of enterprises, and it is more difficult to grasp the evidence of illegal pollution discharge by enterprises (Zhang et al., 2018), which often leads to inefficient environmental governance of “one size fits all.” The NSMF program requires a comprehensive inspection of the standardization of monitoring ports, the

construction of monitoring stations, and the installation of equipment for state-controlled enterprises in the jurisdiction. For those that do not meet the requirements, rectification plans should be listed one by one, and those with serious circumstances should be ordered to withdraw from the market. The installation of automatic monitoring equipment for pollution sources is the installation of a pair of “electronic eyes” on enterprises to implement real-time and continuous remote monitoring of the concentration and discharge of pollutants by enterprises (Fang et al., 2020), which effectively reduces the information asymmetry between local governments and enterprises and deters enterprises from discharging pollutants. At this time, once a company’s illegal discharge behavior is found, it will face administrative penalties and damage to its corporate reputation (Rick et al., 2021; He et al., 2022) or directly affect its eligibility to enjoy relevant preferential policies (Johan and Lans, 2020; Lu, 2022). To prevent this risk, companies have the incentive to improve their environmental performance and achieve their own sustainable development.

Third, the NSMF program can alleviate the principal-agent problem between people and government and between people and enterprises and amplify the deterrent effect of the environmental policy by increasing the participation of the public. On the one hand, the government’s vigorous publicity of the NSMF program and environmental protection has sent a signal to the society that the government attaches importance to environmental protection and has raised the public’s awareness of environmental protection. At the same time, measures such as the real-time disclosure of monitoring information and user satisfaction surveys have lowered the threshold for public participation, activated social supervision networks, and increased public willingness to participate in environmental governance. Increased public environmental awareness and willingness to participate amplifies the deterrent effect on local governments and businesses, which is conducive for the improvement of corporate environmental performance (Kostka and Mol, 2013; Van Rooij, 2016). On the other hand, after an enterprise is included in the national control list, it faces more attention from the market and investors. When the enterprise’s environmental performance is poor, it loses favor of the market and investors. As a “rational economic man,” to maximize profits, enterprises have to make corresponding adaptive behavioral responses under the stimulation of environmental policies and market preferences, take the initiative to reconfigure resources, adopt green innovation and other ways to improve their environmental performance, and improve their market competitiveness. In summary, this article proposes the following hypotheses:

H1. With other conditions unchanged, the NSMF program can significantly improve corporate environmental performance.

3.2 Impact of financing constraints

The heterogeneity of enterprises’ own resources lead to differences in impact of the NSMF program on corporate environmental performance (Fang et al., 2020). From the perspective of cost–benefit theory, the impact of the NSMF program on corporate environmental performance is related to corporate financing constraints. Measures for the Administration of Automatic Monitoring of Pollution Sources (2005) stipulate that the construction, operation, and maintenance of automatic monitoring equipment are self-financed by polluters, and the expenditure of these non-productive activities often crowds out potential investment by companies in expanding production. On the one hand, when the NSMF program is implemented, enterprises with a high degree of financing constraints resist the development of the relevant work of the pollution source monitoring system and in the face of punishment for excessive sewage discharge or the abnormal operation of equipment, there is the idea of “two penalties take the lightest,” that is, deliberately letting equipment failure or even man-made destruction of equipment, rendering the pollution source monitoring instruments useless. On the other hand, the higher the degree of financing constraints of sewage enterprises, the less motivated they become to take the initiative to improve their environmental performance through technological innovation (Tian et al., 2022; Aghion et al., 2016). Therefore, financing constraints may weaken the effect of the NSMF program on corporate environmental performance. In summary, this article proposes the following assumptions:

H2. With other conditions unchanged, compared with enterprises with a higher degree of financing constraints, the NSMF program has a more significant effect on the environmental performance of enterprises with a lower degree of financing constraints.

3.3 Impact of international trade

In the context of globalization, trade openness is an important factor affecting the environment. Therefore, the relationship between the NSMF program and corporate environmental performance will inevitably be affected by international trade. On the one hand, when compared with domestic enterprises, export enterprises face more stringent environmental requirements. In the international market, the requirements for environmental protection in various countries are constantly increasing (Peng et al., 2020), especially in developed countries with higher economic and technological levels, which generally implement higher environmental protection technical standards, such as the “EPA mark” of the United States, the “EV system” of the European Union, the “ECP” of Canada, and the “ecological mark” of Austria, which

makes the export enterprises themselves face more stringent environmental requirements. To meet the environmental standards of the developed countries, export enterprises must reduce pollution to obtain environmental certification of developed countries (Bloom et al., 2013; De Loecker and Goldberg, 2014). On the other hand, when compared with domestic enterprises, international trade has strengthened the technological exchanges between export enterprises and developed countries. Export enterprises can participate in the global export market and have access to the most advanced manufacturing, technology R&D, and management methods of developed countries (Roy and Yasar, 2015). Correspondingly, in the process of expanding and operating export markets in developed countries, export enterprises have the opportunity to obtain more green production technologies to improve their own environmental performance (Zhou et al., 2018). Torres (1999) also pointed out that through free trade, residents' income has increased significantly and more resources and technology can be used to improve the environment. Regardless of whether it is included in the national control list or not, the environmental performance of export enterprises will be better than that of domestic enterprises, so the improvement in the environmental performance of enterprises by the NSMF program is more obvious in domestic enterprises. In summary, this article proposes the following assumptions:

H3. With other conditions unchanged, when compared with export enterprises, the NSMF program has a more significant impact on the environmental performance of domestic enterprises.

3.4 Impact of the economic development level

The level of economic development in the region where the enterprise is located is also an important factor in testing the impact of the NSMF program on corporate environmental performance. The operation of the NSMF program project shows that the central government attaches great importance to local environmental governance, and environmental protection has become one of the important assessment indicators for the promotion mechanism of local officials. However, according to the theory of multi-objective assessment, when the assessed aspect evaluates multiple objectives, it gives priority to achieving goals that are less difficult and more effective (Holmstrom and Milgrom, 1991). When compared with environmental protection goals, the economic growth goals have clearer measurements and more efficient ways of achieving them. Therefore, when the downward pressure on the regional economy increases, the local governments may choose to relax environmental regulations in exchange for economic growth, thereby weakening the motivation of corporate environmental governance. Conversely, when the level of regional

economic development is high, the opportunity cost for local governments to pursue environmental protection goals is small (Tang, 2015). Under the pressure of the NSMF program, local governments can increase their law enforcement efforts and strive to achieve the dual goals of environmental protection and economic growth, thereby enhancing the motivation for corporate pollution control and improving the environmental performance of enterprises. In summary, this article proposes the following assumptions:

H4. With other conditions unchanged, compared with regions with lower levels of economic development, the NSMF program has a more significant effect on corporate environmental performance in regions with higher levels of economic development.

4 Research design

4.1 Sample and data collection

This article mainly uses two types of micro data. One is the enterprise pollution emission data, which is from the China Industrial Enterprise Pollution Database from 1998 to 2010. The database is considered to be the most comprehensive and reliable enterprise-level pollution emission data in China (Zhang et al., 2018). Second, other data at the enterprise level are from the China Industrial Enterprise Database from 1998 to 2013. Referring to the practice of Brandt et al. (2012) and Su (2020), we matched the data of the two databases, eliminating the missing data of enterprise codes, and finally selected the data from 2001 to 2009 as the research sample. At the same time, this article sets the year of policy implementation as 2007 because although the NSMF program's list is dynamically adjusted every year in principle, the list does not change until 2010 when compared with 2007. Therefore, this article sets the treatment group as the enterprises listed on the NSMF program's list in 2007. After eliminating the missing values of the main variables, 10,006 observations were finally obtained. In addition, to control the impact of extreme values, this article winsorizes all continuous variables at the 1% and 99% levels, and all operations are completed using Stata 16.0.

4.2 Model design

To verify H_1 , the following difference-in-differences model was built:

$$EP_{it} (CEP_{it}) = \alpha + \beta_1 Treat_i * Post_t + \beta_2 Controls_i + \lambda + \mu + Year * Province + Industry + \varepsilon_{it}. \quad (1)$$

This article measures corporate environmental performance from the two aspects of emission reduction and energy savings; EP_{it} represents the comprehensive emission intensity of

enterprise i in year t , CEP_{it} represents the unit energy consumption of enterprise i in year t , and $Treat_i$ is a grouping dummy variable—if the enterprise is included in the national control list, it is assigned to 1; if otherwise, it is assigned 0. $Post_t$ is a time dummy variable—if it is in the year of policy implementation in 2007 or after, the value assigned is 1; if otherwise, it is 0. X_i is the control variable, λ is the time fixed effect, μ is the individual fixed effect, and ε_{it} is the random error term. This article focuses on the coefficient β_1 of the cross-term between $Treat_i$ and $Post_t$, which reflects the net impact of the NSMF program on corporate environmental performance. When β_1 is significantly negative, it means that the NSMF program inhibits the comprehensive emission intensity of enterprises or reduces the unit energy consumption of enterprises, that is, it improves the environmental performance of monitored enterprises. In addition, H2, H3, and H4 are tested by grouping.

4.3 Measurement of variables

4.3.1 Dependent variable

The explained variables of this article are of corporate environmental performance (EP_{it} and CEP_{it}). The literature on the measurement of environmental performance can be roughly divided into pollution emission methods, evaluation system methods, ecological benefit methods, environmental capital expenditure methods, etc. Among them, the pollution emission method can be more intuitive and accurate. To measure the environmental performance of enterprises, this article refers to the practice of Su (2020) and selects industrial wastewater, chemical oxygen demand, industrial waste gas, sulfur dioxide, and soot and dust to construct a comprehensive index of enterprise pollution emission intensity and measures the environmental performance of enterprises from the perspective of “emission reduction.” The enterprise comprehensive emission intensity specific calculation formula is as follows:

$$EP_{it} = \frac{1}{n} \sum_{\omega=1}^n (W_{\omega it} \times UP_{\omega it}), \quad (2)$$

where EP_{it} is the enterprise comprehensive pollution intensity, ω denotes the type of pollutant, n denotes the number of pollutant species, w is the adjustment coefficient, represented by the ratio of the emission intensity of various pollutants of the enterprise to the national average, and UP is the dimensionless emission intensity of various pollutants from enterprises after Z-score standardization.

At the same time, to comprehensively measure the environmental performance of corporations, this article also selects the unit energy consumption of enterprises from the perspective of “energy saving.” Since the proportion of coal in

China’s energy consumption is basically maintained at 70%, and China’s coal resources and price advantages make the coal-based energy pattern unchangeable for a long time, the physical quantity of coal can better reflect the energy input of Chinese industrial enterprises. Therefore, this article uses coal consumption to calculate the unit energy consumption (CEP_{it}) of enterprises as another measure of corporate environmental performance.

4.3.2 Independent variable

The independent variable of this article is $Treat*Post$. $Treat$ is a grouping dummy variable, indicating whether the enterprise is included in the NSMF program’s list. If the enterprise is included in the NSMF program’s list, it is defined as the treatment group, and $Treat$ is assigned the value 1, if otherwise, it is assigned the value 0. $Post$ is a time dummy variable that represents the year in which the NSMF program was run. If it is in 2007 and later, $Post$ is assigned a value of 1; if otherwise, it is assigned 0.

4.3.3 Regulated variables

1) Financing constraints (FC): this article uses the SA index method to calculate the financing constraints of enterprises and divides the samples into a higher financing constraint group and a lower financing constraint group according to the median of the SA index. If it is less than the median, it is the lower financing constraint group, and the FC assignment is 1. If it is greater than the median, it is the higher financing constraint group, and the FC assignment is 0. The SA index is calculated as follows:

$$SA = 0.737*Size + 0.043*Size^2 - 0.04*Age. \quad (3)$$

2) Export/domestic (IM): according to the export volume of the enterprise, whether the enterprise participates in international trade is judged. If the export volume of the enterprise is greater than 0, it indicates that the enterprise is an export enterprise, and the IM assignment is 1; if otherwise, it is 0.

3) Regional economic development level (PGDP): in this paper, the *per capita* GDP at the city level is used to measure the economic development level of each region. Based on the median, the samples are divided into groups with higher economic development levels and lower economic development levels. If it is greater than the median, it indicates that the economic development level of the region is higher, and the PGDP is assigned 1; if otherwise, it is 0.

4.3.4 Control variables

This article selects company size (Size), nature of ownership (Soe), company age (Age), financial leverage (Lev), profitability (Roa), fresh water in industrial water (Water), number of

TABLE 1 Definition of primary variables.

Variable type	Variable name	Variable symbol	Variable declaration
Dependent variable	Comprehensive discharge intensity	<i>EP</i>	$EP_{it} = \frac{1}{n} \sum_{w=1}^n (W_{wit} \times UP_{wit})$
	Unit energy consumption	<i>CEP</i>	Total coal consumption tons/total industrial output value
Independent variable	Group virtual variable	<i>Treat</i>	If the enterprise is included in the national control list, the value is 1; otherwise, it is 0
	Time virtual variable	<i>Post</i>	In 2007 or later, the value is 1; otherwise, the value is 0
Regulated variables	Financing constraints	<i>FC</i>	If it is lower than the median of SA index, it is assigned a value of 1; otherwise, it is 0
	Export/domestic enterprises	<i>IM</i>	If the export amount of the enterprise is greater than 0, the value is 1; otherwise, it is 0
	Level of regional economic development	<i>PGDP</i>	GDP per capita of each city/10,000. If it is higher than the median, the assigned value is 1; otherwise, it is 0
Control variables	Enterprise size	<i>Size</i>	Natural log of total assets in millions at the year end
	Financial leverage	<i>Lev</i>	Total liabilities at year/year-end assets
	Return on assets	<i>Roa</i>	Year-end net profit/year-end total assets
	Nature of property right	<i>Soe</i>	If the enterprise is state owned, the value is 1; otherwise, it is 0
	Enterprise age	<i>Age</i>	Natural logarithm of the company's founding years
	Fresh water consumption in industrial water use	<i>Water</i>	Fresh water consumption in industrial water (ton)/100,000
	Total number of employees at the end of the year	<i>Employee</i>	Average annual number of employees (10,000 persons)
	Number of pollutant processing equipment	<i>Equipment</i>	Number of wastewater treatment facilities + waste gas treatment facilities + desulfurization facilities

pollutant handling facilities (Equipment), and year-end total employees (Employee) as the control variables. At the same time, the interaction term Year*Province is added to the model to control the unobservable factors that change over time at the regional level. Specific variable definitions are shown in Table 1.

4.4 Descriptive statistics

Table 2 reports the descriptive statistics of the whole sample of the main variables. The mean value of the comprehensive index (EP) of enterprise pollution emissions is 3.074, the standard deviation is 13.620, and the maximum and minimum values are 95.200 and -0.031, respectively. The mean value of unit energy consumption (CEP) is 4.260, the standard deviation is 6.734, and the maximum and minimum values are 43.190 and 0, respectively, indicating that the environmental performance of the industrial enterprises in China is good, but there are great differences between different individuals. The average value of Treat is 0.176, that is, 17.6% of the enterprises are included in the NSMF program's list, which also shows that the overall

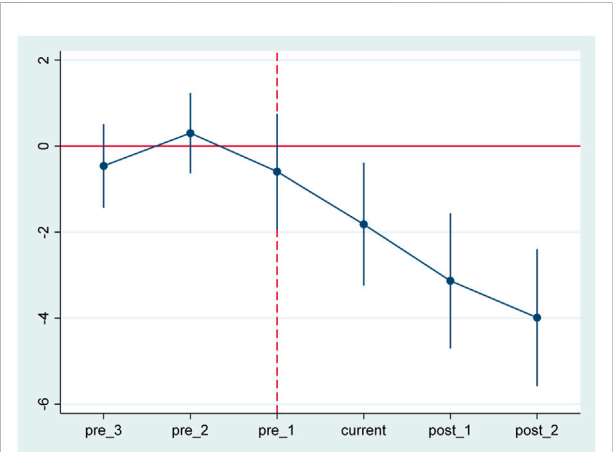


FIGURE 1
Parallel trend test.

environmental performance of China's industrial enterprises is good. The descriptive statistical values of the other variables are reasonably distributed and will not be repeated here.

TABLE 2 Descriptive statistical analysis.

Variable	N	Mean	50%	Std. dev.	Min	Max
EP	10,006	3.074	-0.004	13.620	-0.031	95.200
CEP	10,006	4.260	1.357	6.734	0.000	43.190
Treat	10,006	0.176	0.000	0.381	0.000	1.000
Post	10,006	0.277	0.000	0.448	0.000	1.000
IM	10,006	0.740	1.000	0.439	0.000	1.000
FC	10,006	0.509	1.000	0.500	0.000	1.000
PGDP	10,006	1.613	1.299	1.070	0.416	5.047
Size	10,006	4.818	4.664	1.900	0.824	8.288
Lev	10,006	0.651	0.650	0.273	0.027	1.590
Roa	10,006	0.029	0.011	0.096	-0.237	0.702
Age	10,006	2.390	2.398	1.129	0.000	4.111
Soe	10,006	0.242	0.000	0.428	0.000	1.000
Employee	10,006	0.176	0.046	0.393	0.004	2.716
Equipment	10,006	10.410	6.000	11.610	0.000	40.000
Water	10,006	11.850	1.800	22.820	0.000	83.640

TABLE 3 Baseline regression results.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	EP	EP	EP	CEP	CEP	CEP
Treat*Post	−1.177**	−1.526***	−2.035***	−0.570**	−0.607**	−0.607**
	(−2.453)	(−3.173)	(−4.057)	(−2.079)	(−2.184)	(−2.048)
Size		−0.378	−0.564**		−0.033	0.011
		(−1.488)	(−2.192)		(−0.222)	(0.074)
Lev		0.441	0.324		−0.252	−0.220
		(0.728)	(0.533)		(−0.721)	(−0.612)
Roa		0.344	0.371		−0.574	−0.474
		(0.275)	(0.290)		(−0.794)	(−0.627)
Age		0.144	0.182		−0.214*	−0.222*
		(0.736)	(0.917)		(−1.891)	(−1.891)
Soe		−0.982	−0.683		−0.217	−0.130
		(−1.640)	(−1.120)		(−0.628)	(−0.361)
Employee		−1.405	−1.350		−0.259	−0.091
		(−1.218)	(−1.116)		(−0.389)	(−0.127)
Equipment		0.056**	0.068***		−0.024*	−0.023*
		(2.365)	(2.838)		(−1.734)	(−1.650)
Water		0.050***	0.046***		0.001	−0.000
		(3.646)	(3.337)		(0.064)	(−0.004)
Constant	2.822***	3.604***	6.854	4.987***	5.895***	−19.885
	(12.948)	(2.658)	(0.053)	(40.072)	(7.526)	(−0.261)
Year*Province	No	No	Yes	No	No	Yes
Year	Yes	Yes	No	Yes	Yes	No
Firm	Yes	Yes	Yes	Yes	Yes	Yes
N	10,006	10,006	10,006	10,006	10,006	10,006
Adj-R ²	0.004	0.030	0.109	0.028	0.030	0.068

Note: ***, **, and * are significant at the levels of 1%, 5%, and 10%, respectively, with T values in brackets. The same is given below.

5 Analyses and results

5.1 Parallel trend test

The premise of the difference-in-differences method is that the enterprises included in the NSMF program’s list and the enterprises not included in the NSMF program’s list meet the parallel trend hypothesis before the project runs. To this end, this article draws on the event research method of Li et al. (2016) for a parallel trend test. On the basis of model (1), the window period for variables of 1–3 years before the operation year of

the NSMF program and the window period for variables of 1–2 years after the operation are added. The following regression model is set as

$$EP_{it} = \alpha + \beta_1 Treat_i * pre\_1 + \beta_2 Treat_i * pre\_2 + \beta_3 Treat_i * pre\_3 + \beta_0 Treat_i * current + \beta_4 Treat_i * post\_1 + \beta_5 Treat_i * post\_2 + \beta_6 Controls_i + year * province + Industry + \lambda + \mu + \varepsilon_{it}.$$

(4)

After adding the control variables, the regression coefficients of the explanatory variables $Treat_i * pre\_1$, $Treat_i * pre\_2$, and $Treat_i * pre\_3$ were not significant,

TABLE 4 NSMF program, financing constraints, and corporate environmental performance.

Variable	Low financing constraint				High financing constraint			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	EP	EP	CEP	CEP	EP	EP	CEP	CEP
Treat*Post	−1.773**	−2.179***	−0.663**	−0.863***	−0.193	−0.194	−0.505	−0.132
	(−2.452)	(−2.882)	(−2.280)	(−2.786)	(−0.511)	(−0.436)	(−0.657)	(−0.152)
Size	−0.144	−0.455	0.130	0.139	−0.017	−0.044	−0.083	0.041
	(−0.267)	(−0.810)	(0.598)	(0.603)	(−0.126)	(−0.296)	(−0.294)	(0.142)
Lev	1.100	1.051	−0.539	−0.516	0.268	0.287	0.720	0.608
	(0.877)	(0.826)	(−1.068)	(−0.990)	(1.041)	(1.053)	(1.371)	(1.143)
Roa	0.586	−0.309	−0.636	−0.724	0.101	0.050	−0.735	0.328
	(0.199)	(−0.101)	(−0.537)	(−0.577)	(0.205)	(0.092)	(−0.729)	(0.312)
Age	0.447	0.450	−0.227*	−0.151	−0.002	0.025	−0.327	−0.041
	(1.330)	(1.297)	(−1.678)	(−1.059)	(−0.019)	(0.231)	(−1.569)	(−0.190)
Soe	−0.819	−0.189	−0.154	−0.069	−0.258	−0.062	−0.658	−0.322
	(−0.938)	(−0.209)	(−0.437)	(−0.188)	(−0.540)	(−0.117)	(−0.676)	(−0.315)
Employee	−0.283	−0.556	−0.253	0.057	−4.036	−3.438	1.229	2.183
	(−0.183)	(−0.336)	(−0.406)	(0.084)	(−0.846)	(−0.677)	(0.126)	(0.220)
Equipment	0.070**	0.097***	−0.036**	−0.041***	−0.005	0.010	0.005	0.014
	(1.962)	(2.643)	(−2.513)	(−2.718)	(−0.287)	(0.520)	(0.131)	(0.389)
Water	0.050***	0.046**	−0.008	−0.012	0.063***	0.066***	0.068**	0.057*
	(2.626)	(2.372)	(−1.055)	(−1.450)	(4.427)	(4.428)	(2.309)	(1.960)
Constant	3.084	−5.859	4.604***	−44.440	0.162	1.322	6.139***	10.035
	(0.872)	(−0.026)	(3.236)	(−0.477)	(0.287)	(0.023)	(5.322)	(0.090)
Year*Province	No	Yes	No	Yes	No	Yes	No	Yes
Year	Yes	No	Yes	No	Yes	No	Yes	No
Firm	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	5,003	5,003	5,003	5,003	5,003	5,003	5,003	5,003
Adj-R ²	0.036	0.153	0.053	0.135	0.021	0.099	0.027	0.178

indicating that at least 3 years before the implementation of the policy, the trend of the pollutant discharge intensity and unit energy consumption of the treatment group and control group had been consistent, meeting the parallel trend hypothesis. To show the results more intuitively, we drew a graph as shown in Figure 1. It can be seen that before the operation of the national control project, the regression coefficients of $Treat_i \cdot pre\_1$, $Treat_i \cdot pre\_2$, and $Treat_i \cdot pre\_3$ are not significantly different from 0 (95% confidence interval contains 0), indicating that there is no significant

difference between the treatment group and control group before the operation of the program, which satisfies the parallel trend hypothesis, while the coefficient after the operation of the project is significantly negative, indicating that the operation of the NSMF program has a negative impact on the pollutant discharge and unit energy consumption of the enterprise, that is, it improves the environmental performance of the enterprise [due to space limitations, this article only selects the report model (4) which includes more intuitive graphics].

TABLE 5 NSMF program, import/export enterprises, and corporate environmental performance.

Variable	Import enterprise				Export enterprise			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	EP	EP	CEP	CEP	EP	EP	CEP	CEP
Treat*Post	−1.886***	−1.650***	−0.847**	−0.810*	−0.479	−1.623	−0.272	−0.350
	(−3.929)	(−3.261)	(−2.103)	(−1.832)	(−0.466)	(−1.472)	(−0.881)	(−1.049)
Size	0.016	−0.121	−0.186	−0.137	−1.131	−0.856	0.283	0.398
	(0.067)	(−0.497)	(−0.923)	(−0.645)	(−1.359)	(−0.979)	(1.136)	(1.505)
Lev	0.201	0.314	−0.127	−0.148	2.092	1.695	−0.886	−0.970
	(0.385)	(0.607)	(−0.290)	(−0.328)	(1.097)	(0.836)	(−1.550)	(−1.582)
Roa	−0.721	−0.627	−0.488	−0.494	7.706	6.664	−1.713	−0.869
	(−0.702)	(−0.605)	(−0.567)	(−0.546)	(1.515)	(1.239)	(−1.123)	(−0.534)
Age	0.291	0.324	−0.325**	−0.325*	−0.018	−0.065	0.037	0.034
	(1.481)	(1.631)	(−1.974)	(−1.870)	(−0.040)	(−0.136)	(0.275)	(0.238)
Soe	0.822	0.532	−0.211	−0.099	−3.124**	−2.852**	−0.112	−0.165
	(1.274)	(0.814)	(−0.391)	(−0.174)	(−2.527)	(−2.128)	(−0.301)	(−0.408)
Employee	5.490***	7.992***	−0.005	−0.010	−0.293	−1.696	0.035	−0.138
	(2.758)	(3.755)	(−0.003)	(−0.005)	(−0.119)	(−0.627)	(0.047)	(−0.169)
Equipment	0.046*	0.047*	−0.031	−0.023	0.059	0.088*	−0.019	−0.023
	(1.910)	(1.948)	(−1.545)	(−1.094)	(1.150)	(1.650)	(−1.207)	(−1.420)
Water	0.041***	0.045***	−0.003	0.004	0.082**	0.070**	0.011	0.014
	(3.026)	(3.295)	(−0.266)	(0.335)	(2.524)	(2.045)	(1.160)	(1.337)
Constant	−0.994	4.268	7.422***	−16.807	11.269**	8.999	1.273	−0.321
	(−0.823)	(0.046)	(7.326)	(−0.208)	(2.018)	(0.136)	(0.760)	(−0.016)
Year*Province	No	Yes	No	Yes	No	Yes	No	Yes
Year	Yes	No	Yes	No	Yes	No	Yes	No
Firm	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	7,407	7,407	7,407	7,407	2,599	2,599	2,599	2,599
Adj-R ²	0.028	0.172	0.036	0.108	0.029	0.215	0.027	0.200

5.2 Baseline regression results

The regression results of the basic relationship between the NSMF program and corporate environmental performance are shown in Table 3. Specifically, the regression results of the influences of the NSMF program on the comprehensive pollutant emission intensity of the enterprises are listed in columns (1)–(3). The regression results of the influences of the NSMF program on unit energy consumption of the enterprises are listed in

columns (4)–(6). Control variables are added in column (3) and column (6). After time, individual and industrial fixed effects as well as regional unobservable factors that change with time are controlled, and the coefficients of Treat*Post are −2.035 and −0.607, which are significantly negative at the 5% level at least. Based on the aforementioned results, the implementation of the NSMF program inhibits the comprehensive pollutant emission intensity of enterprises and lowers their unit energy consumption, thus improving the enterprise environmental performance. Hence, H₁ is

TABLE 6 NSMF program, economic development level, and corporate environmental performance.

Variable	High economic development level				Low economic development level			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	EP	EP	CEP	CEP	EP	EP	CEP	CEP
Treat*Post	−2.070***	−2.657***	−0.450	−0.448	−1.476	−1.461	−0.676	−0.619
	(−3.614)	(−4.518)	(−1.329)	(−1.241)	(−1.247)	(−1.178)	(−0.837)	(−0.728)
Size	−0.297	−0.409	0.080	0.013	−0.065	−0.119	−0.396	−0.212
	(−0.968)	(−1.347)	(0.439)	(0.070)	(−0.150)	(−0.267)	(−1.350)	(−0.691)
Lev	0.093	0.183	−0.424	−0.472	0.782	0.734	−0.048	0.093
	(0.120)	(0.239)	(−0.922)	(−1.005)	(0.887)	(0.818)	(−0.079)	(0.152)
Roa	0.089	0.833	−0.852	−0.873	−0.549	−1.408	1.852	2.825
	(0.066)	(0.621)	(−1.073)	(−1.062)	(−0.224)	(−0.552)	(1.108)	(1.614)
Age	0.559**	0.655**	−0.293*	−0.324**	−0.061	−0.130	−0.113	−0.117
	(2.126)	(2.495)	(−1.883)	(−2.016)	(−0.200)	(−0.406)	(−0.539)	(−0.533)
Soe	−3.229***	−2.893***	0.637	0.519	0.372	0.487	−0.378	−0.228
	(−3.233)	(−2.886)	(1.079)	(0.844)	(0.454)	(0.578)	(−0.676)	(−0.394)
Employee	3.142**	4.004***	−0.629	−0.262	7.208***	7.847***	0.057	−0.244
	(2.221)	(2.718)	(−0.753)	(−0.290)	(3.187)	(3.306)	(0.037)	(−0.150)
Equipment	0.069**	0.079***	−0.006	−0.011	0.088**	0.089**	−0.018	−0.014
	(2.286)	(2.645)	(−0.354)	(−0.575)	(2.247)	(2.241)	(−0.682)	(−0.520)
Water	0.027	0.011	−0.014	−0.015	−0.012	−0.013	0.020	0.016
	(1.491)	(0.598)	(−1.282)	(−1.341)	(−0.528)	(−0.585)	(1.286)	(1.013)
Constant	3.346**	1.388	5.046***	4.588***	0.350	1.383	7.558***	6.240***
	(2.011)	(0.767)	(5.127)	(4.135)	(0.155)	(0.548)	(4.910)	(3.604)
Year*Province	No	Yes	No	Yes	No	Yes	No	Yes
Year	Yes	No	Yes	No	Yes	No	Yes	No
Firm	Yes	Yes	Yes	Yes	Yes	YES	Yes	Yes
N	4,962	4,962	4,962	4,962	5,044	5,044	5,044	5,044
Adj-R ²	0.040	0.151	0.026	0.074	0.022	0.069	0.028	0.064

verified. Such an effect of the NSMF program is analyzed as follows. First, the NSMF program can decrease information asymmetry between the central government and local government and between the government and enterprises. It can deter enterprises and local governments such that the government can formulate more specific environmental regulations and facilitate full implementation to force enterprises to adopt energy savings and emission reduction. Second, it can strengthen the environmental protection consciousness of enterprises through information

transmission and thereby strengthen their willingness to improve clean production technologies, purchase environmental protection equipment, and produce green products. Third, the NSMF program brings an innovative idea of environmental management and improves the overall environmental supervision and law enforcement efficacy. All of these factors facilitate the improvement of enterprise environmental performance and bring a new situation of energy savings and emission reduction in China.

TABLE 7 Robustness test.

Variable	(1)	(2)	(3)	(4)	(5)
	EP	CEP	EP	CEP	LnCOD
Treat*Post	−0.168	−0.035	−1.377***	−0.610**	−0.187**
	(−0.368)	(−0.132)	(−2.896)	(−2.193)	(−2.022)
Size	−0.056	0.020	−0.421*	−0.032	0.069
	(−0.274)	(0.167)	(−1.677)	(−0.216)	(1.408)
Lev	0.656	−0.068	0.528	−0.255	0.041
	(1.357)	(−0.242)	(0.882)	(−0.728)	(0.351)
Roa	1.392	−0.508	0.871	−0.585	−0.074
	(1.321)	(−0.825)	(0.702)	(−0.807)	(−0.306)
Age	−0.120	−0.063	0.141	−0.213*	0.037
	(−0.827)	(−0.747)	(0.729)	(−1.883)	(0.982)
Soe	−0.710	−0.136	−0.977*	−0.215	−0.071
	(−1.438)	(−0.471)	(−1.650)	(−0.623)	(−0.615)
Employee	−0.102**	−0.009	−0.010	−0.003	0.311
	(−2.453)	(−0.381)	(−0.880)	(−0.431)	(1.403)
Equipment	0.086***	0.000	0.056**	−0.024*	0.011**
	(4.239)	(0.024)	(2.400)	(−1.731)	(2.485)
Water	0.048***	−0.013**	0.050***	0.001	0.026***
	(4.282)	(−2.035)	(3.697)	(0.066)	(9.787)
Constant	−2.299	19.900***	3.672***	5.894***	8.299***
	(−0.453)	(6.708)	(2.739)	(7.518)	(31.808)
Year	Yes	Yes	Yes	Yes	Yes
Firm	Yes	Yes	Yes	Yes	Yes
N	10,006	10,006	9,995	9,995	10,006
Adj-R ²	0.089	0.092	0.027	0.030	0.039

5.3 Heterogeneity analysis

5.3.1 NSMF program, financing constraint, and corporate environmental performance

To test whether the influences of the NSMF program on corporate environmental performance are impacted by financing constraints, sample data are divided into a low financing constraint group and high financing constraint group in this study. The regression results are shown in Table 4. Columns (1), (2), (5), and (6) are the “emission reduction” effect of the NSMF program. After relevant factors are controlled, the Treat*Post coefficients of the low financing constraint group and high financing constraint group are -2.179 and -0.194 , respectively. The former is significantly negative at the 1% level, while the latter is not significant. Columns (3), (4), (7), and (8) are the “energy saving” effect of the project. After relevant factors are controlled, the Treat*Post coefficients of the low financing constraint group and high financing constraint group are -0.863 and -0.132 , respectively. The former is significantly negative at the 1% level, while the latter is not significant. Based on the aforementioned results, the NSMF program decreases the comprehensive pollutant emission intensity and unit energy consumption of the enterprises with low financing constraints. However, it fails to exert significant effects on the “emission reduction” and “energy saving” of the enterprises with high financing constraints. In other words, the NSMF program improves the environmental performance of enterprises with low financing constraints more significantly than that of enterprises with high financing constraints. Hence, H_2 is verified. According to the analysis, enterprises with high financing constraints may decrease investment in environmental protection to the maximum extent and reject the installation and maintenance of automatic pollution source supervision equipment due to financial pressure. From the perspective of the “rational economic man,” the primary goal of enterprises with high financing constraints is to expand production. Only enterprises with low financing constraints have enough capital and motivation to improve clean production technologies and make innovations in green production activities.

5.3.2 NSMF program, import/export enterprises, and corporate environmental performance

To test whether the influences of the NSMF program on corporate environmental performance are impacted by domestic marketing or export properties, sample data are divided into domestic marketing enterprise group and export enterprise group in this study. The regression results are shown in Table 5. Columns (1) and (2) of Table 5 show that the Treat*Post coefficients for the group of domestic firms are -1.886 and -1.650 , which are significantly negative at the 1% level. Columns (3) and (4) show that the Treat*Post coefficients for the group of domestic firms

TABLE 8 NSMF program, investment, and corporate environmental performance.

Variable	(1)	(2)	(3)
	EP	Invest	EP
Treat*Post	-1.944^{***}	0.373^{**}	-1.941^{***}
	(-3.957)	(2.104)	(-3.947)
Invest			-0.008
			(-0.170)
Size	-0.264	0.206^{**}	-0.262
	(-1.016)	(2.195)	(-1.008)
Lev	0.441	0.173	0.442
	(0.715)	(0.779)	(0.717)
Roa	0.570	0.002	0.570
	(0.452)	(0.004)	(0.452)
Age	0.234	-0.260^{***}	0.232
	(1.158)	(-3.564)	(1.145)
Soe	-1.316^{**}	-0.058	-1.317^{**}
	(-2.081)	(-0.256)	(-2.082)
Employee	-0.212	-0.407^{**}	-0.215
	(-0.430)	(-2.293)	(-0.436)
Export	-1.047	0.655	-1.042
	(-0.872)	(1.513)	(-0.867)
Water	0.050^{***}	-0.003	0.049^{***}
	(6.306)	(-0.899)	(6.302)
Constant	-4.313	1.183	-4.303
	(-0.889)	(0.676)	(-0.887)
Year	Yes	Yes	Yes
Firm	Yes	Yes	Yes
N	10,006	10,006	10,006
Adj-R ²	0.068	0.084	0.068

are -0.847 and -0.810 , respectively, which are significantly negative at the 5% and 10% levels, while the Treat*Post coefficients for the group of exporting firms are not significant. It shows that the NSMF program significantly reduces the comprehensive emission intensity and unit energy consumption of domestic enterprises and not only promotes “energy conservation and emission reduction” of domestic enterprises but also has no significant effect on export enterprises, which verifies H_3 . According to the analysis, when compared with domestic enterprises, export enterprises face more stringent environmental requirements. To meet the

TABLE 9 Bootstrap regression results.

Intermediary path	Effect value	Confidence interval
NSMF program → invest → corporate environmental performance	0.769***	[0.422,1.115]

environmental standards of developed countries, export enterprises must reduce pollution to obtain environmental certification of developed countries. In addition, when participating in the global export market, export enterprises can access the most advanced production and manufacturing, technology research and development, and management methods of developed countries. When compared with domestic enterprises, export enterprises have the opportunity to obtain more green production technologies to improve their own environmental performance. Therefore, the NSMF program can better promote the improvement of environmental performance of domestic enterprises.

5.3.3 NSMF program, economic development level, and corporate environmental performance

The level of economic development in the location of the enterprise also restricts the decision-making of resource allocation. In this article, the sample data are divided into higher level economic development group and lower level economic development group. The regression results are shown in Table 6. Columns (1) and (2) of Table 6 show that the NSMF program significantly reduces the comprehensive emission intensity of enterprises in regions of higher economic development levels and has no significant inhibitory effect on the unit energy consumption of enterprises in the region nor has any significant impact on the environmental performance of enterprises in regions of lower economic development levels. This may be because in areas with low levels of economic development, the primary task of the local governments is to promote economic development due to the pressure of performance appraisal, thus increasing the bargaining power of heavily polluting enterprises and ultimately weakening the improvement effect of state-controlled projects on the environmental performance of local enterprises.

5.4 Robustness test

5.4.1 Placebo test

For the sake of robustness, this article refers to Tang et al. (2022) and conducts a counterfactual test by changing the policy implementation time of the NSMF program. To exclude the influence of other policies and random factors, this article assumes that the NSMF program was implemented in 2005. If the regression results show that the coefficient of

Treat*Post is no longer significant, then the improvement in corporate environmental performance comes from the implementation of the NSMF program. Columns (1) and (2) of Table 7 provide the regression results of the policy implementation point for 2005. The results show that if the NSMF program is implemented in 2005, the cross term of Treat*Post is no longer significant whether the dependent variable is the comprehensive emission intensity of the enterprise or the unit energy consumption of the enterprise, excluding the influence of other policies and random factors, confirming that the improvement of corporate environmental performance comes from the implementation of the NSMF program.

5.4.2 PSM-DID

To eliminate “selection bias” of the control group and treatment group, the reliability of the conclusions in this study was further verified by PSM-DID. All control variables were used as covariants during propensity score matching. The key monitored enterprises and the remaining enterprises were matched, and the observation values that failed to meet the common area hypothesis were eliminated. Finally, 9,995 observation values were obtained. The control group was built by nearest neighbor matching, and the matching ratio was 1:1. Moreover, DID model regression was carried out based on the matched samples. The regression results are shown in columns (3) and (4) of Table 7. Clearly, the Treat*Post coefficients of the explained variables, comprehensive pollutant emission intensity, and unit energy consumption are all significantly negative. The results are also robust, which is consistent with the conclusions of this study.

5.4.3 Replace dependent variable

Zhang et al. (2018) noted that chemical oxygen demand is a pollutant emitted by most industrial enterprises, which has become a key indicator of routine monitoring in China and a key indicator of the environmental performance of local governments in China. Therefore, to ensure the robustness of the aforementioned results, this article refers to the research of Zhang et al. (2018) and uses the emissions of chemical oxygen demand of enterprises as an alternative variable of environmental performance. The regression results are listed in column (5) of Table 7. The results show that the coefficient of Treat*Post is -0.187 , which is still significantly negative at the 5% level, indicating that the NSMF program has significantly improved the environmental performance of enterprises, which is consistent with previous conclusions.

5.5 Mechanism test

Previously, it has been confirmed that the NSMF program can significantly reduce the comprehensive emission intensity and unit energy consumption of enterprises and improve the environmental performance of enterprises. So how is this achieved? In the aforementioned theoretical analysis and research hypothesis section, it is mentioned that the NSMF program can not only alleviate information asymmetry but also effect signal transmission and rule of law. These characteristics force enterprises to install automatic monitoring equipment and carry out environmental governance. Specifically, within the enterprise, resources may be reconfigured, such as purchasing more environmental protection equipment to improve the environmental performance. Therefore, this article takes “waste gas treatment capacity” as the proxy variable of enterprise environmental protection investment to test whether the NSMF program can reduce its comprehensive emission intensity and unit energy consumption by increasing the investment in enterprise environmental protection equipment. Following [Wen and Ye \(2014\)](#), we set the following model:

$$EP_{it}(CEP_{it}) = \alpha + cTreat_i * Post_t + \beta_2 Controls_i + \lambda + \mu + Year * Province + Industry + \varepsilon_{it}, \quad (5)$$

$$Invest_{it} = \alpha + aTreat_i * Post_t + \beta_2 Controls_i + \lambda + \mu + Year * Province + Industry + \varepsilon_{it} \quad (6)$$

$$EP_{it}(CEP_{it}) = \alpha + c'Treat_i * Post_t + bInvest_{it} + \beta_2 Controls_i + \lambda + \mu + Year * Province + Industry + \varepsilon_{it} \quad (7)$$

where Invest is the enterprise environmental protection equipment investment calculated from “enterprise waste gas treatment facilities processing capacity (in standard cubic meters)/100,000.” Eq. 5 tests the impact of the NSMF program on corporate environmental performance, which has been verified above. Eq. 6 tests the influence of the NSMF program on enterprise environmental protection equipment input and observes the significance of coefficient a. Eq. 7 takes the NSMF program and enterprise environmental protection equipment input as core explanatory variables for regression to observe the significance of coefficients c' and b. If coefficients a and b are significant and coefficient c' is significant, it indicates that the investment in environmental protection equipment is a part of the mediator. If the coefficient c' is not significant, it indicates that the investment in environmental protection equipment is a complete intermediary. If at least one of the coefficients a and b is not significant, the bootstrap method should be used for further testing. The regression results are shown in [Table 8](#). The results show that the coefficient of invest is not significant, so it is necessary to further conduct the bootstrap test. The bootstrap test results ([Table 9](#)) show that the indirect

effect of enterprise environmental protection equipment investment on the improvement of corporate environmental performance of the NSMF program is significant. This indicates that the increase in investment in environmental protection equipment is a non-exclusive intermediary mechanism for the NSMF program to improve corporate environmental performance.

6 Conclusion and implications

6.1 Conclusion

In China, the realization of the central ecological environment governance goal deeply depends on the transformation mechanism of the environmental policy implementation chain at the local level. However, under the state of incomplete information and the incentive structure of multitasking principal-agent, there are many principal-agent problems which lead to the destruction of the transformation mechanism of the policy implementation chain and the failure to achieve the goal of environmental governance. In view of this, based on the Chinese industrial enterprise pollution database and the Chinese industrial enterprise database, this article selects industrial enterprise data from 2001 to 2009 as the research sample, empirically tests the impact and mechanism of the NSMF program on the environmental performance of enterprises, and further examines the different effects of enterprise heterogeneity and regional differences on the relationship between the two. The empirical results show the following: 1) the implementation of the NSMF program has significantly improved corporate environmental performance. 2) When compared with enterprises with a high degree of financing constraints, the NSMF program has a more significant effect on the environmental performance of enterprises with a low degree of financing constraints; when compared with export enterprises, the NSMF program has a more significant effect on the environmental performance of domestic enterprises; when compared with enterprises with a lower economic development level in the region, the NSMF program has a more significant effect on the environmental performance of enterprises with a higher economic development level in the region. 3) The mechanism tests show that the NSMF program can improve environmental performance by increasing investment in environmental protection equipment.

6.2 Practical implications

The conclusion of this study has important policy implications for optimizing China's future environmental governance. First, the central government should strengthen local environmental supervision. On the one hand, more

flexible and comprehensive central supervision and environmental decentralization of environmental policies should be adopted. For many years, the ambiguity and conflict of China's environmental regulations have tended to stimulate the interest game between the local government and central government in the implementation process. Therefore, it is urgent to use modern means to improve the intensity and precision of environmental governance to reduce the space of discretion in the implementation of environmental policies and exercise authority. On the other hand, the proportion of the environmental governance effect in the promotion assessment of local officials should be increased. The monitoring data of the NSMF program are integrated with the environmental governance data obtained by "man-marking" to comprehensively evaluate the environmental governance performance of all provinces and regions, ranking them regularly, rewarding provinces with good environmental control, and increasing punishment for provinces with poor environmental control to correct the GDP-only mentality of local governments.

Second, we fully consider the possible impact of heterogeneity of the enterprise's own resources. First, the construction of an environmental credit rating system should be strengthened for domestic enterprises or enterprises with higher financing constraints. Governments should provide appropriate economic resources, such as environmental subsidies, tax rebates, and even cooperation opportunities, to encourage the sustainable implementation of environmentally friendly behavior for reputable exporters who voluntarily fulfill their environmental responsibilities or those with higher financing constraints. Second, domestic enterprises or enterprises with higher financing constraints should be encouraged to coordinate with universities and research institutions. The government should give certain subsidies and rewards to this series of cooperation, minimize the investment and risk of green technology R&D of domestic enterprises or enterprises with higher financing constraints, and reduce their cost pressure in improving environmental performance. Third, China's international division of labor status should be enhanced. On the one hand, in facing the new situation of economic globalization, we should continue to promote the process of opening up to the outside world, implement a more active export strategy, make full use of the regional cooperation platform built by the "Belt and Road," and encourage enterprises to participate in globalization to higher and higher levels. On the other hand, the construction of an enterprise resource sharing network encourages export enterprises and domestic enterprises to engage in green technology exchange and emission reduction equipment sharing and promote enterprise green technology progress and emission reduction equipment upgrades to obtain more environmental benefits.

Third, we should strengthen the application effect of monitoring data and improve our environmental

monitoring system. On the one hand, we should give full play to the unique advantages of the NSMF program and eliminate information noise and other interference factors caused by the principal-agent relationship in environmental governance to ensure the integrity and smoothness of the implementation chain of environmental policies and ultimately maximize the effect of the environmental governance system. On the other hand, the data monitored by the NSMF program should be widely used in all walks of life. The wide application of monitoring data will improve the public's attention to the performance of corporate social responsibility, promote the public's wide participation in environmental governance, and facilitate government managers, enterprises, and scholars in various fields to explore the path of green development.

6.3 Limitations and future research

While this study validates the target findings, it also has certain limitations that need to be addressed in future research. First, the data selected in this article are all from the Chinese industrial enterprise pollution database and the Chinese industrial enterprise database, which is considered to be the most comprehensive and reliable environmental microeconomic data in China. However, data from both databases are not updated to the most recent year. In the future, we can further explore how to measure corporate environmental performance more intuitively using the latest data. Second, there is the intermediary effect. This study not only focuses on the intermediary role of investment in environmental protection equipment but also shows that investment in environmental protection equipment is not the only intermediary mechanism by which the NSMF program improves enterprises' environmental performance. Future research can explore the synergy mechanism of the NSMF program affecting enterprises' environmental performance. Finally, there is a balance between environmental performance and economic performance. Although the NSMF program is essential to alleviate the principal-agent problem in the process of corporate environmental governance and can effectively improve the environmental performance of enterprises, it is still necessary to explore whether the NSMF program can improve the environmental performance of enterprises while considering economic performance to make the research conclusion 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 author.

Author contributions

All authors have contributed to the study of concepts and design. TZ, CX, and HL conceived and designed the research, analyzed the data, and wrote and revised the manuscript. JL proofread and edited the manuscript.

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The impact of temperature on labor productivity—evidence from temperature-sensitive enterprises

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Climate change increases the frequency of extreme climate events and impacts the economy and the society in a negative way. As typical climate events, temperature anomalies affect individual health and working conditions, particularly for industries that depend heavily on temperatures. Using a research setting of Chinese temperature-sensitive enterprises, we analyze the impact of temperature on labor productivity. The findings indicate an inverse U-shaped relationship between temperature and labor productivity, with labor productivity peaking at 24.90°C on average. Further analysis shows that labor productivity peaks in the eastern regions at a higher level (26.25°C) than in the central and western regions (20°C). Moreover, we note that technological innovation is crucial for enterprises to manage climate risks and maintain effective labor productivity. This study provides empirical evidence on the relationship between environmental risk and corporate operations, shedding light on the significance of corporate sustainable development against accelerating global climate change.

KEYWORDS

climate change risk, extreme weather, temperature anomalies, labor productivity, technological innovation

1 Introduction

Climate change, which continues to have an effect on ecosystems and socioeconomic systems, is one of the largest problems facing the globe today (Selvi et al., 2019; He et al., 2021; Hong et al., 2021; Sebestyén et al., 2021; Yu et al., 2022; Zhang et al., 2022). Global warming, environmental pollution, deforestation, soil degradation, and prolonged droughts are just a few of the significant environmental problems that have frequently surfaced along with explosive economic growth during the past few decades. These extreme events endangered human survival and caused great economic losses (Marengo et al., 2021; Sohail et al., 2022). For example, Typhoon Hagibis in 2019 brought more than 240 mm of extreme rainfall in Japan, leading to around 100 deaths and adding \$4 billion to Japan's economic losses (Wagner, 2022). According to the Global Climate Risk Index 2020, Germany's hot weather in 2018 caused 70% of the soil to be affected by drought, resulting in a total of EUR 3 billion (US \$3.54 billion) in damage.

Some scholars believe that human activities have caused greenhouse gas emissions to increase annually, making climate change often associated with temperature anomalies (Sakhel, 2017; Kouloukoui et al., 2019; Uzar, 2020; Chen et al., 2022; Shi et al., 2022). A large body of research has empirically shown that temperature anomalies can have a wide range of negative impacts, including harm to people's physical and mental health (Deschenes, 2014; Carleton and Hsiang, 2016; Zhang et al., 2018; Fishman et al., 2019). The body temperature increases and physiological functions such as water and salt metabolism, circulation, and respiration would be disrupted in an environment with extremely high temperatures (Venugopal et al., 2020). High temperatures affect productivity by reducing human body load endurance and work efficiency while increasing operation errors and accident rates (Li et al., 2009; Somanathan et al., 2021). In an environment with extremely low temperatures, human body temperature will drop, triggering a series of protective or compensatory physiological responses, such as increased metabolic rate and accelerated heart rate and respiratory rate (McInnes et al., 2017). Long-term exposure to low temperatures can lower tactile discrimination and significantly reduce limb operating flexibility, thus reducing labor productivity (Varghese et al., 2019). In conclusion, temperature anomalies would interfere with the body's thermal equilibrium and lower labor productivity.

According to the endogenous growth theory (Romer, 1990), labor input determines the level of industrial development since workforce productivity reflects the organization's output capacity. Based on this, the economic concept of labor productivity—the ratio of total product output to labor input—is adopted (Hanna et al., 2005). Therefore, depending on how labor productivity is calculated, both high and low temperatures negatively impact the level of labor input and labor productivity. But Matsumoto (2019) demonstrated that labor productivity in medium-temperature zones is higher. As confirmed by Burke et al. (2015), economic productivity is non-linear in temperature. So, because people prefer moderate temperatures to extreme temperatures, there might be a non-linear link between temperature and labor productivity.

Understanding how temperature affects industrial sector, and in particular how it affects labor productivity, has become an issue of economic significance. In this paper, we examine the impact of temperature on labor productivity using construction enterprises as the research setting, as building construction tasks often take place outdoors, making labor productivity more susceptible to temperature anomalies (Blaauw et al., 2022; Feller and Vaseva, 2014; Yu et al., 2021). According to Tan and Abdul-Samad (2022), extreme temperature events would decrease labor force and hinder construction projects. The workforce reduction will hinder progress, shut down operations, reduce work efficiency, and decrease labor productivity (Gasparrini et al., 2015; Morabito et al., 2017;

Dosio et al., 2018; Watts et al., 2019). So, temperature anomalies can make the construction industry more vulnerable to adverse circumstances.

We choose construction enterprises in 31 provinces in mainland China as the research setting for two reasons. On one hand, the geographic locations of provinces in mainland China span from 73°40' east longitude of Xinjiang Uygur Autonomous Region to 135°2'30" east longitude of Heilongjiang province, and from 3°52' north latitude of Hainan province to 53°33' north latitude of Heilongjiang province. So, the country has a broad temperature range, which satisfies our criteria for the variation of temperature data. On the other hand, the development of building procedures and mechanical equipment over the past few decades has greatly increased the overall productivity of the Chinese construction sector (Tian et al., 2020; Xue et al., 2022), which is still highly labor-intensive. Construction workers work outdoors and are more sensitive to temperature changes. So, we analyze the effect of temperature on labor productivity by using the data of construction enterprises from 2006 to 2019 in 31 provinces of mainland China. The results show an inverse U-shaped relationship between labor productivity and temperature. The labor productivity of construction enterprises is highest at an average temperature of 24.9°C and will decrease when temperatures are too high or too low. Then, the optimum temperature for labor productivity is higher in Eastern China (26.25°C) than in Central and Western China (20°C). In addition, we conduct a test for heterogeneity in technological innovation level and find that it significantly and positively affects the relationship between temperature and labor productivity.

The primary contributions of this paper are manifested in the following two aspects. On one hand, we demonstrate an inverse U-shaped relationship between temperature and labor productivity by using a sample with a wide range of temperature spans. Scholars have conducted numerous studies on how temperature affects construction labor productivity, but the majority of them focused on the effect of high temperatures on the human body (Chinnadurai et al., 2016; Li et al., 2016). In the absence of research on the effect of low temperatures, those findings could hardly reflect the changes in construction labor productivity caused by temperature differences. On the other hand, unlike studies where temperature and labor productivity data were obtained from a small number of construction contractors (Mohamed and Srinavin, 2005; Mathee et al., 2010; Nasirzadeh and Nojehi, 2013; Blaauw et al., 2022), we extend our study from the site level to the construction company level. This makes the findings generalizable and convincing. Therefore, this research could help businesses develop better strategies to deal with temperature fluctuations and increase labor productivity, which will improve their competitiveness and maintain sustainable growth.

In the remainder of this paper, section 2 is the literature review on the impact of temperature on labor productivity in the construction enterprise. Section 3 introduces the methodology,

including data collection and the spatial econometric model. Section 4 presents the descriptive statistical analysis and the regression results. The analysis includes baseline regression analysis, heterogeneous regression analysis in terms of geographical effects, and robustness checks. Section 5 discusses the findings and future research direction. Section 6 concludes this article.

2 Literature review

Climate change has been hastened by rapid industrialization and urbanization (Tao et al., 2022). It has raised the risk for companies operating throughout the world. (Liu et al., 2021; Wan et al., 2021; Tian et al., 2022; Wagner, 2022). For example, extreme weather events associated with flooding have a significant impact on the operation of insurance enterprises (Cremades et al., 2018), and severe drought raises a company's cost of equity capital (Huynh et al., 2020). Understanding the impact of temperature changes on enterprises is crucial because it is predicted that global temperatures will continue to change drastically (Stern and Kaufmann, 2014; Malhi et al., 2021). Especially for enterprises whose core operations depend on natural conditions, temperature changes can have a detrimental effect on an enterprise's financial performance, such as loss of physical assets and increased labor costs (Sun et al., 2020).

The construction industry is vulnerable to climate change risks because of its dependence on temperature and seasonal conditions. Most construction work is conducted outdoors and is labor-intensive, so workers' health and productivity are directly affected by temperature changes (Grifoni et al., 2021). Kim and Hong's (2020) thermal evaluation questionnaire results indicated that humans function most efficiently and comfortably at 25°C. But extreme temperatures affect workers' health and working conditions, which then lowers labour productivity in the construction industry. These effects include high-temperature and low-temperature effects.

Based on the relationship between environmental temperature and human thermal balance, Zhu and Zhao (2006) defined high-temperature environments as either a residential environment above 35°C or a working environment above 32°C. The human body responds to thermal stress in a high-temperature environment by releasing heat to keep itself in balance. However, agricultural and construction workers frequently wear personal protective gear and clothes, especially when engaging in outside tasks. This can dramatically reduce body heat loss and increase heat stress (Grifoni et al., 2021). When air temperature approaches or exceeds skin temperature (31°C–32°C), it is almost ineffective for the human body to dissipate heat through natural air convection; instead, sweat evaporation takes over as the primary method of heat dissipation (Hargreaves, 2008). If

water loss from sweat evaporation is not replenished in time, it might cause dehydration, heatstroke, heat cramps, cardiovascular disease, or even death (Venugopal et al., 2020). In addition, uncomfortable outdoor working circumstances in hot weather may affect construction workers' willingness and capacity to work (Somanathan et al., 2021). Li et al. (2016) examined the relationship between working hours and temperature using field data from a reinforced concrete construction project in Beijing, China. The findings showed that the percentage of real working hours drops by 0.57 percent on average for every 1°C increase in temperature. Reduced nerve and muscle excitability in workers, as well as irritability and anxiety, could increase accident rates and decrease labor productivity (Li et al., 2009).

Recently, Adhvaryu et al. (2020) utilized energy-efficient LED lighting to create temperature fluctuations in the workplace and concluded that worker productivity would increase when the temperature decreases moderately. It's noteworthy that extremely low temperatures are more harmful to health than high temperatures (Gasparrini et al., 2015; King et al., 2020). Low-temperature environment increases energy consumption, decreases tactile sensitivity, and damages the cardiovascular and cerebrovascular vessels (McInnes et al., 2017). Research by Varghese et al. (2019) has shown that low temperatures are mostly to blame for the nearly 5% of workplace accidents in Australia that are caused by ambient temperature. Especially, the outdoor work of construction enterprises is closely related to the natural environment and climatic conditions. Therefore, the reduction of ambient temperature usually directly affects the occupational sector in a negative way (Moda et al., 2019). Additionally, at low temperatures, equipment performance degrades more rapidly (Fiorese et al., 2015). All of these could reduce labor productivity and safety in the construction enterprise.

Many scholars have analyzed the impact of temperature on construction workers, in order to find the ideal temperature for boosting labor productivity. The majority of these studies focused on the study of the effects of high temperatures. For example, Li et al. (2016) measured and compared rebar workers' performance between 2:00 pm and 3:00 pm and 7:00 pm to 9:00 pm in the summer (representing high ambient temperatures). By analyzing data from four construction sites, Mohamed and Srinavin (2005) confirmed the negative impact of high temperatures on construction labor productivity. Similarly, Chinnadurai et al. (2016) noted that working outdoors performing light and heavy construction tasks in high ambient temperatures above 28°C resulted in an 18%–35% reduction in overall worker productivity. At the same time, we find that many studies take a city or even a construction site as the research setting. For example, Mathee et al. (2010) found that sun-exposed workers in Johannesburg and Uppington experience work-related discomfort and ill health in hot weather, and Nasirzadeh and Nojehdehi (2013) used on-site data from a real

housing construction project to develop a quantitative model of labor productivity.

Overall, researchers show that temperature conditions impose substantial economic and social burdens on enterprises. However, research on the quantitative effects of temperature remains limited and flawed. The problem with the aforementioned studies is that they only consider the high-temperature data while ignoring the low-temperature data, which can lead to biased results. Also, since the data were primarily field data for a specific construction project or city, there may have been representative errors in the choice of construction contractors, possibly leading to big measuring errors in labor productivity data. Therefore, this paper attempts to contribute by examining the effects of both high and low temperatures on labor productivity in the construction sector. To ensure the generalizability of the results for the construction industry, we select a temperature dataset with a large temperature span and collect enterprise labor productivity data from the provincial level.

3 Methodology

3.1 Data collection

We take atmospheric temperature as the key explanatory variable. Li et al. (2016) used the QUESTemp³⁶ thermal environment monitor to obtain on-site air temperature data. But this method of gathering field data only records the high-temperature environment for a set amount of time. By collecting data on average temperature across provinces, which includes both low and high temperatures, we could measure the effect of a wider range of temperatures. Besides, we take construction labor productivity as the dependent variable. According to the International Labour Organization, labor productivity is the gross domestic product (or value-added) per worker (Kpogonon et al., 2022). This economic concept is also used to define construction labor productivity. In this paper, we use the construction labor productivity data from the National Bureau of Statistics of China (NBS), which is calculated as the ratio of the total output value of construction enterprises to the number of laborers in enterprises. Labor productivity changes at the micro level of firm and project activities make up the overall construction industry productivity (Abdel-Wahab and Vogl, 2011). Construction labor productivity data reflects the average labor productivity level of construction enterprises in a province, which can enhance the generalizability of the model's findings.

Economic situations and weather conditions are two driving factors that could affect enterprise labor productivity (Durdyev et al., 2018; Avotra et al., 2021; Somanathan et al., 2021; Xiao and You, 2021). Therefore, we added seven economic and weather

attributes, including regional gross domestic product (GDP), total output value of the construction industry, number of construction practitioners, relative humidity, wind speed, rainfall, and Sun exposure, as control variables. The sample period is from 2006 to 2019, and the data frequency is quarterly. The data are sourced from the published data of the National Bureau of Statistics of China and the China Meteorological Data Centre. The definition and measurement of variables are shown in Table 1. To ensure that the data follow a normal distribution, we took the logarithm of regional GDP and sunshine hours.

3.2 Model settings

Compared to traditional econometric models, the spatial econometric model takes into consideration the spatial dependences among neighboring regions (Anselin, 2002). The results generated by the spatial model are more precise when spatial factors play a role in the focal causal relationship. To verify the existence of spatial dependence between labor productivity and its influencing factors in the construction industry, we first conducted a spatial autocorrelation test on the residuals obtained from the ordinary least squares (OLS) regression. The results showed that the p -value of Moran's I statistic is 0.000, rejecting the null hypothesis of spatial autocorrelation. The results indicated the existence of a spatial dependence; therefore, spatial econometric model is more suitable to implement the estimations. Following mainstream spatial econometrics literature (e.g., Anselin, 2002, 2003), we chose the binary geographical adjacent weight matrix with one representing neighboring provinces and 0 otherwise. The spatial weight matrix is defined as follows:

$$\omega_{ij} = \begin{cases} 1, & \text{region } i \text{ is geographically adjacent to region } j; \\ 0, & \text{otherwise.} \end{cases}$$

The spatial econometric model has two widely-used types: the spatial lag model (SLM) and the spatial error model (SEM). The model forms of SLM and SEM are:

$$Y = \rho WY + X\beta + \varepsilon, \varepsilon \sim N[0, \sigma^2 I] \quad (1)$$

$$Y = X\beta + \varepsilon, \varepsilon = \lambda W\varepsilon + \mu, \mu \sim N[0, \sigma^2 I] \quad (2)$$

where Y denotes the dependent variable; X represents the independent variables; W refers to the aforementioned spatial weight matrix; β is the coefficients of X , reflecting the influence of independent variables on dependent variable; ρ represents the spatial correlation coefficient of Y ; λ is the correlation coefficient of the spatial error; and ε and μ are random errors following the multivariate normal distribution. The selection of whether to use SLM or SEM as the final regression model is determined by the results of the Lagrange Multiplier and Robust Lagrange Multiplier tests (Anselin, 2002).

TABLE 1 Variable descriptions.

Variables	Definition	Measurement
Construction labor productivity	The efficiency of the construction labor force in producing construction products	Construction industrial product/Total construction labor force
Average temperature	The arithmetic mean of the observed atmospheric temperature values	$\sum$ Average of day's high and low temperatures/number of days in the quarter
Regional GDP	The final result of production activities of all resident units in a region	$\sum$ Total output of all industries – $\sum$ Intermediate input of all industries
Total output value of the construction industry	The sum of construction industry products and services produced by construction enterprises in a certain period of time expressed in monetary terms	Construction project output value + equipment installation project output value + other output value
Number of construction practitioners	People who work in social groups or enterprises or institutions in the construction industry and get paid	–
Relative humidity (%)	The arithmetic mean of the observed relative humidity	$\sum$ Average of day's relative humidity/number of days in the quarter
Wind speed (m/s)	The arithmetic mean of the observed wind speed	$\sum$ Average of day's wind speed/number of days in the quarter
Rainfall ≥ 0.1 mm (day)	Number of days with rainfall ≥ 0.1 mm	–
Sunshine hours (hour)	The arithmetic mean of the observed sunshine duration	$\sum$ Average of day's sunshine hours/number of days in the quarter

TABLE 2 Descriptive statistics.

Variables	Label	Min	Max	Mean	Std. Dev	Cov (%)
Construction labor productivity (ten thousand yuan/person)	Lp	0.89	27.20	8.52	3.84	45.07
Average temperature (°C)	Atem	–14.97	29.70	14.28	9.84	68.91
Regional GDP (hundred million yuan)	Gdp	4.01	10.32	7.99	1.11	13.89
Total output value of the construction industry (hundred million yuan)	Tov	0.91	12,421.40	1,142.90	1,417.26	124.01
Number of construction practitioners (ten thousand people)	number	0.22	918.60	127.97	139.51	109.02
Relative humidity (%)	humidity	24.33	91.30	65.32	13.52	20.70
Wind speed (m/s)	Wind	0.30	5.10	2.09	0.68	32.54
Rainfall ≥ 0.1 mm (day)	rainfall	0.60	71.00	25.08	14.83	59.13
Sunshine hours (hour)	sunshine	3.03	14.51	5.96	0.69	11.58

4 Results

4.1 Descriptive statistics

Descriptive statistics of all variables are reported in [Table 2](#). It indicates that the minimum quarterly Chinese construction labor productivity over the period 2006–2019 in the 31 provinces is 8,900 yuan/person, the maximum is 272,000 yuan/person, the mean value is 85,200 yuan/person, and the standard deviation is 38,400 yuan/person. And the minimum quarterly average temperature of the 31 provinces is –14.97°C, the maximum is 29.70°C, the mean value is 14.28°C, and the standard deviation is

9.84°C. The last column in [Table 2](#) displays the coefficient of variation (Cov), which makes the variations of all variables comparable by eliminating scale difference. It is calculated by dividing standard deviation by mean. So compared to other variables, the total output value of the construction industry, the number of construction practitioners, and rainfall have larger variations in terms of the Cov. There are also large variations in average temperature and construction labor productivity. However, the variations of sunshine hours, regional GDP, relative humidity, and wind speed are relatively small.

As reported in [Figure 1](#), the highest quarterly average temperature of the 31 provinces is in the third quarter over the

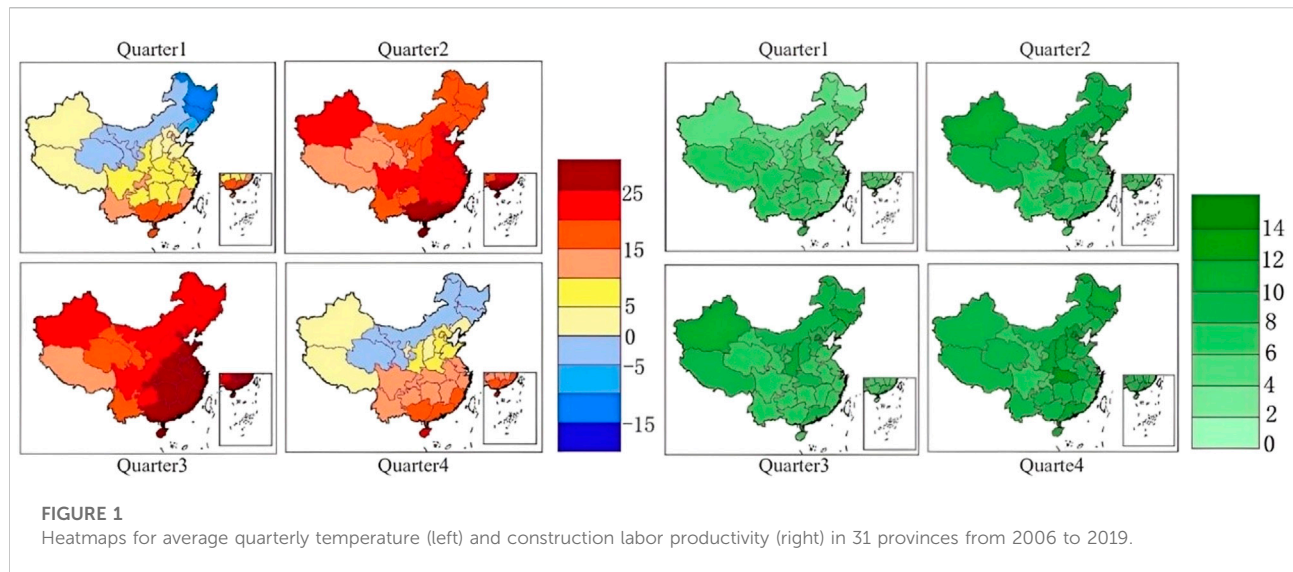


TABLE 3 Model selection test statistical results.

Test	Test statistic	p-value
Lagrange Multiplier (SLM)	34.838	0.000
Robust LM (SLM)	3.950	0.047
Lagrange Multiplier (SEM)	422.240	0.000
Robust LM (SEM)	391.352	0.000

period 2006–2019, followed by the second quarter. And the variations in these two-quarters are relatively small. The first quarter has the lowest average temperature and the largest variation. Construction labor productivity is also the lowest in the first quarter, but the variation is the smallest. Compared with the first quarter, the other three-quarters have higher labor productivity, but the variations are larger.

4.2 Baseline regression results

We select the final regression model between SLM and SEM using results of the Lagrange Multiplier (LM) and Robust LM tests. The higher the test statistics, the better the model. The results in Table 3 indicate that SEM passed both Lagrange Multiplier and Robust LM tests (p -value < .001) and the test statistics of SEM are much greater than that of SLM. Meanwhile, according to untabulated Hausman test results and statistics from LogLikelihood Ratio, AIC, and SC, this paper chose SEM as the final model for empirical analyses.

Therefore, the spatial econometric model specification for examining the impact of temperature on construction labor productivity is:

$$lp_{it} = \beta_1 atem_{it} + \beta_2 atem_{it}^2 + \beta_3 tov_{it} + \beta_4 lngdp_{it} + \beta_5 number_{it} + \beta_6 humidity_{it} + \beta_7 wind_{it} + \beta_8 rainfall_{it} + \beta_9 lnsunshine_{it} + StateFE + TimeFE + \varepsilon_{it}$$

$$\varepsilon_{it} = \lambda W\varepsilon_{it} + \mu$$

where lp_{it} refers to the construction labor productivity of province i in time t ; $atem_{it}$ is the average temperature of province i in time t ; tov_{it} , $lngdp_{it}$, $number_{it}$, $humidity_{it}$, $wind_{it}$, $rainfall_{it}$ and $lnsunshine_{it}$ represent control variables introduced in Table 2, respectively. We also control for time-invariant attributes of the provinces ($StateFE$) and time fixed effect ($TimeFE$). The other parameters follow the same explanations of Eq. 2. As discussed in the theoretical analysis, labor productivity is likely to follow an inverse U-shaped relationship with temperature, i.e., the productivity raises when temperature increases from extremely cold to the optimum temperature where productivity reaches the highest and begins to decrease when temperature is higher than the optimum temperature and reaches the lowest when it is extremely hot. Therefore, we introduced its squared term ($atem_{it}^2$) in the regression model to test the inverse U-shaped relationship. We use Stata software to obtain the parameter estimates and the results are reported in Table 4.

The coefficients of $atem$ and $atem^2$ are 0.2191 (p -value < .001) and -0.0044 (p -value < .001), indicating an inverse U-shaped relationship between temperature and construction labor productivity. The results also show that the spatial error correlation coefficient (λ) is greater than 0 and highly significant (p -value < .001), indicating that other factors that are not included in the model have spatial spillover effects on construction labor productivity in neighboring regions. In addition, among the control variables, the total output value of the construction industry (tov) and regional GDP ($lngdp$) have

TABLE 4 Results for spatial econometric regression.

Variables	All areas	Eastern China	Central and western China
Atem	0.2191*** (17.16)	0.2100*** (8.53)	0.2080*** (13.98)
atem ²	−0.0044*** (−9.27)	−0.0040*** (−3.38)	−0.0052*** (−9.41)
Tov	0.0025*** (28.79)	0.0022*** (18.60)	0.0031*** (23.55)
Lngdp	1.9964*** (9.52)	3.4100*** (7.80)	1.3990*** (5.76)
Number	−0.0388*** (−30.75)	−0.0372*** (−21.55)	−0.0458*** (−22.75)
humidity	0.0008 (0.16)	0.0217* (2.23)	−0.0148* (−2.40)
Wind	0.1481 (1.85)	0.1970 (1.40)	0.1010 (1.04)
Rainfall	0.0003 (0.08)	−0.0040 (−0.50)	0.0023 (0.47)
Insunshine	0.1597 (2.04)	0.1970 (1.38)	0.1310 (1.47)
λ	0.1406*** (4.31)	−0.0019 (−0.04)	0.1660*** (4.02)
N	1736	616	1,120
R ²	0.6882	0.7617	0.6850

* $p < .05$; ** $p < .01$; *** $p < .001$; t-values are provided in parentheses.

significant and positive effects on construction labor productivity. The number of construction practitioners (*number*) has a significant but negative impact on construction labor productivity; that is, excessive employment in the construction industry reduces labor productivity.

As illustrated in Figure 1, there are notable temperature differences between Eastern China and Central and Western China, with the Eastern region generally having higher temperatures. Therefore, the impact of temperature on labor productivity may vary. Further, we investigate the variability of the inverse U-shaped temperature-productivity nexus in Eastern China and the rest of China (Central and Western China). The regression results for Eastern China and Central and Western China are reported in Table 4.

The results show that the inverse U-shaped relationship between temperature and construction labor productivity is observed in all parts of China. Specifically, in Eastern China, the coefficients of *atem* and *atem*² are 0.2100 (p -value $< .001$) and -0.0040 (p -value $< .001$), respectively; while in the rest of China, the respective coefficients are 0.2080 (p -value $< .001$) and -0.0052 (p -value $< .001$). In addition, the spatial error correlation coefficient (λ) of eastern provinces is not significant, but that of central and western provinces is positive (0.1660) and highly significant (p -value $< .001$), indicating a positive spillover effect from construction labor productivity of neighboring regions to the focal region of central and western China. In terms of control variables, the total output value of the construction industry, the number of employees in the construction industry and regional GDP all significantly impact labor productivity of the construction industry. And regional GDP in eastern regions has a much greater influence than that of central and western regions.

Except for humidity, weather variables have no significant impact on construction labor productivity.

To calculate the optimum temperature that works best for labor productivity in construction industry, we take the derivative of the regression model with all control variables equal to mean values. The derivative calculation shows that when the average temperature is 24.90°C, construction labor productivity reaches the highest. Following the same derivative calculation process, we get the optimum temperature for construction labor productivity in Eastern China is 26.25°C, and 20°C in the rest of China. We thus draw the U-shaped curve between temperature and predicted construction labor productivity in Figure 2, where Figure (A) shows the inverted U-shaped curve for all regions, Figures (B) and (C) show the Eastern and Central and Western China, respectively.

4.3 Heterogeneity analysis of technological innovation level

Construction labor productivity relies heavily on the level of organizational technology (Ercan, 2019). Innovative technologies improve the working and living conditions of workers, which may have an important impact on the relationship between temperature and labor productivity. Therefore, we collect China's regional innovation capability index (*inno*) as a proxy variable for the regional technological innovation level and test the significance of the level of technological innovation. The data are sourced from the China Regional Innovation Capability Evaluation Report, and the sample period is 2006–2019. After that, we also took logarithms of the data.

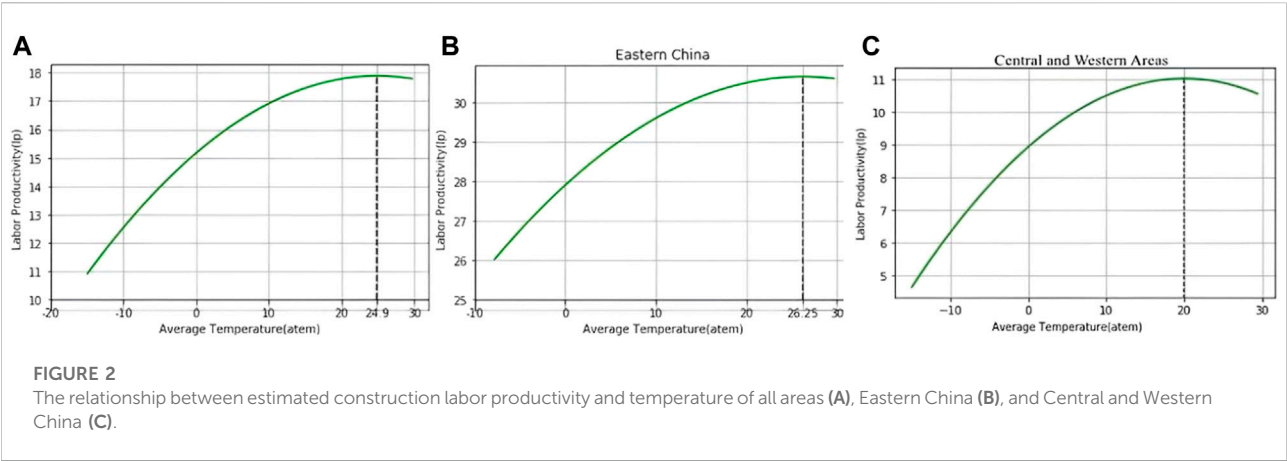


TABLE 5 Results for regression of technological innovation level, temperature and labor productivity.

Variables	Coefficient
Atem	0.3065** (2.50)
atem ²	−0.0122*** (−2.97)
Ininno	1.1747** (2.47)
atem*Ininno	−0.0263 (−0.68)
atem ² *Ininno	0.0022* (1.71)
Tov	0.0025*** (29.12)
Lngdp	1.8272*** (8.22)
number	−0.0394*** (−31.34)
humidity	−0.0011 (−0.21)
Wind	0.1594** (2.02)
rainfall	−0.0001 (−0.03)
Insunshine	0.1642** (2.13)
Λ	0.0405*** (5.05)
N	1736
R ²	0.4663

* $p < .05$; ** $p < .01$; *** $p < .001$; t-values are provided in parentheses.

Referring to Li et al. (2008), we add the interaction term of technological innovation level (*inno*) with temperature (*atem*) and the square of temperature (*atem*²) to the first model in Table 4 to perform the heterogeneity analysis of regional technological innovation level. The results are reported in Table 5. The results show that the coefficient of the interaction term between *atem*² and *inno* is 0.0022, which is significant at the 10% level. This indicates that the technological innovation level significantly affects the relationship between temperature and labor productivity. So, higher level of technological innovation leads to a flatter curve shape (Haans et al., 2016).

4.4 Robustness checks

To check the robustness of our key findings, we use alternative measures of independent variable and add control variable to re-estimate the baseline regressions. Specifically, we use the quarterly lowest temperature (*MINT*) and highest temperature (*MAXT*), instead of average temperature, to re-examine the relationship between temperature and construction labor productivity. The results for robustness tests are displayed in Table 6. It is apparent that both results are consistent with the baseline finding, supporting the inverse U-shaped relationship between temperature and construction labor productivity. Therefore, our empirical evidence about the inverse U-shaped temperature-productivity nexus in the construction industry is robust and valid. The derivative calculation results show that when minimum temperature is 21.45°C or maximum temperature is 28.27°C, construction labor productivity reaches the highest. In addition, it has been shown that the production scale affects labor productivity by increasing the efficiency of using production tools and processing raw materials (Bárány and Siegel, 2021). So, we add a proxy variable for production size, construction completion value *per capita* (completion) to the regression analysis to test whether there are missing factors in the model. The results show that this variable does not affect the fit of the model or the significance of the independent variables. This suggests that the relationship we obtain between temperature and labor productivity is robust.

5 Discussion

Studies in the physiology and engineering literature have discovered that temperature anomalies have a negative impact on individual health and productivity, particularly for construction workers engaged in outside projects (Kjellstrom et al., 2009). To investigate the effect of temperature on labor productivity, we

TABLE 6 Results for robustness checks.

Variables	MINT	MAXT	Add completion
Atem			0.2225*** (18.00)
atem ²			−0.0044*** (−9.37)
Mint	0.1630*** (12.48)		
mint ²	−0.0038*** (−9.20)		
Maxt		0.2940*** (18.15)	
maxt ²		−0.0052*** (−9.79)	
completion			0.3205*** (8.70)
Tov	0.0025*** (28.85)	0.0024*** (28.74)	0.0024*** (28.26)
Lngdp	1.9390*** (9.19)	2.1110*** (10.10)	1.8769*** (9.13)
number	−0.0389*** (−30.69)	−0.0387*** (−30.70)	−0.0372*** (−29.69)
humidity	−0.0052 (−0.98)	0.0064 (1.18)	0.0000 (0.01)
Wind	0.1490 (1.85)	0.1710* (2.14)	0.1720* (2.21)
rainfall	−0.0013 (−0.30)	0.0013 (0.30)	−0.0008 (−0.19)
Insunshine	0.1680* (2.14)	0.1270 (1.63)	0.1422* (1.87)
Λ	0.139*** (4.25)	0.150*** (4.64)	0.0366*** (4.57)
N	1736	1736	1736
R ²	0.6953	0.7086	0.4955

* $p < .05$; ** $p < .01$; *** $p < .001$; t-values are provided in parentheses.

analyze data on construction enterprises from 2006 to 2019 in 31 provinces across Mainland China and separately for Eastern and Central and Western China. Further, we explore the impact of technological innovation on the temperature-labor productivity relationship. The findings are robust and valid.

5.1 Discussion of baseline results

We propose and testify an inverse U-shaped link between temperature and labor productivity. The empirical analysis results show that, in the low-temperature range, as the temperature rises, labor productivity will rise; however, once the temperature reaches the “ideal level”, further temperature rises will cause a decline in labor productivity. The “ideal level” of temperature, that is, the temperature corresponding to the peak of labor productivity is 24.90°C. This is consistent with Kim and Hong (2020)’s finding that employees are most productive when the temperature is around 25°C. Considering the different climates in China, we divide the provinces into Eastern China and Central and Western China before performing the model estimation. The results show that the inverse U-shaped relationship

between temperature and labor productivity still exists in different regions. But labor productivity peaks at 20°C in Central and Western China and at 26.25°C in Eastern China. The difference in optimum temperature may be due to the fact that workers in areas with hotter temperatures (Eastern China) are more accustomed to hot weather and are better adapted to heat stress than workers in other areas (Zhu et al., 2021). Therefore, workers in Eastern China are more tolerant to high temperatures and they could reach peak labor productivity at higher temperatures.

Temperature changes affect every construction worker, and a large number of affected individuals could have a substantial overall impact on construction output. An uncomfortable temperature environment may exacerbate enterprise labor productivity loss by reducing labor intensity in construction activities and the amount of labor available (Carleton and Hsiang, 2016). As climate change poses serious risks to businesses, proactive and appropriate measures are naturally required in response to these risks (Xue et al., 2021; Han et al., 2022; Liu et al., 2022; Wang, 2022). For example, by modifying work hours and work shifts, construction contractors could reduce workers’ work time and intensity on high-temperature days in summer and low-temperature days in winter. By regularly educating construction workers on how to avoid accidents in

extreme temperatures, it is also beneficial in lowering the detrimental effects of extreme temperatures on labor output.

5.2 Discussion of technological innovation impact results

Considering the difference in regional levels of technological innovation in China and its impact on construction labor productivity, we further analyze whether technological innovation level affects the relationship between temperature and labor productivity. The heterogeneity test result suggests that high levels of technological innovation capability can make the inverse U-shaped curve between temperature and labor productivity smoother, reducing the volatility brought by temperature to labor productivity.

There are significant regional differences in the level of economic development and the rate of technological progress in China (Su et al., 2020), which also leads to differences in the level of technological innovation between different regions. Innovative technologies can create more advanced production machines and safer construction equipment, improving the comfort and safety aspects of the working environment (Du et al., 2022). By providing advanced production tools, innovative technologies can mitigate the negative effects of unfavorable conditions and help enterprises maintain greater levels of labor productivity when temperature changes dramatically. So, businesses should strive to strengthen technological innovation and integrate it into every aspect of engineering management.

5.3 Future research direction

Our study is limited by data availability, so future studies related to this paper could be improved in the following ways. First, neuroscience and psychology theories indicate that temperature affects labor productivity by influencing one's physical and mental state. This implies that the collection of relevant physiological data on the human body allows the study of medically mediated effects between temperature and labor productivity. Second, the labor productivity of enterprises may also be related to other personal characteristics of construction workers, such as gender difference and education level of workers. Future research could try to obtain quarterly data on variables of construction workers' personal characteristics in each firm to expand the control variables in this regard. Finally, considering the different climates and temperatures in China, scholars could also study the mechanisms of temperature effects on workers from a climatological perspective.

6 Conclusion

Climate change often puts businesses under a considerable amount of pressure. Nowadays, global temperatures fluctuate frequently, which destroys the working environment and physical conditions of workers and lowers labor productivity. We take Chinese construction enterprises as the research setting to examine the effect of temperature on labor productivity, and divide provinces into Eastern and Central and Western to study the temperature-productivity relationship separately. In terms of variability in the level of technological innovation, we examine the effect of technological innovation on the temperature-productivity relationship. For validity and reliability, we also implement robustness tests. The empirical results demonstrate that: 1) There is an inverse U-shaped relationship between temperature and labor productivity. The labor productivity in construction enterprises reaches its highest when the average temperature is 24.90°C, and corrodes when the temperature is either too high or too low. 2) The optimum temperature for labor productivity in Eastern China is 26.25°C, and 20°C in Central and Western China. 3) Technological innovation may mitigate the adverse effects of temperature fluctuations by providing advanced equipment, thus helping enterprises maintain greater levels of labor productivity. This paper confirms the impact of temperature on labor productivity and offers empirical support for subsequent steps to lessen the negative impact of temperature on enterprise labor productivity. It also offers a basis for policy-making related to the health issues of laborers, especially outdoor workers.

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

WZ: methodology, validation, supervision. ND: methodology, formal analysis, writing—review and editing. YH: software, writing—review and editing. JH: data curation, writing—original draft preparation. NZ: software, formal analysis, writing—original draft preparation. All authors have read and agreed to the published version of the manuscript.

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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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How to drive corporate responsible innovation? A dual perspective from internal and external drivers of environmental protection enterprises

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Responsible innovation has been widely concerned by the public sector and actively explored by scholars for its great role in supporting eco-innovation and sustainable development. However, as the main body of innovation, enterprises have not been fully recognized. Moreover, the research on the driving factors of responsible innovation is mostly the direct influence of a single factor, lacking the overall consideration of the internal and external environment. To bridge this research gap, this study, by deeply interviewing 13 entrepreneurs in environmental protection enterprises, clarified the concept of corporate responsible innovation and its four-dimensional framework (inclusion, anticipation, reflexivity, responsiveness), and then proposed the MPN-MSE driving factor model of corporate responsible innovation from the internal and external perspectives. The external factors include market pressure (M), policy pressure (P), and normative pressure (N), while the internal factors include responsible innovation motivation (M), responsible innovation system (S), and responsible innovation elements (E). The research findings provide an important theoretical contribution to the research of corporate responsible innovation.

KEYWORDS

corporate responsible innovation, environmental protection enterprises, drivers, dual perspective, construct

1 Introduction

Responsible Innovation (RI), which was first proposed in the EU ([Horizon, 2020](#)) framework program, emphasizes the establishment of an open, interactive and transparent innovation process in which innovation actors share responsibility with social actors, attempting to rationally embed scientific and technological progress in the evolution of social development and to guide innovation processes and products towards ethical acceptability, development sustainability and social satisfaction to address the social impacts of innovation and the latest technological advances ([Owen et al., 2012](#); [Schomberg, 2012](#); [Christofi et al., 2022](#)). Corporate social responsibility has become an

important factor for enterprises to achieve sustainable management (Lee and Jeong, 2022). As the main body of innovation, enterprises are also the main body of implementing responsible innovation, which plays important role in promoting the research and practice of responsible innovation. This is particularly representative of environmental protection enterprises because sustainable development can be achieved by deepening into more effective and eco-friendly products and technologies (Moldes et al., 2013). Environmental protection has always been the focus of social concern, which will affect the sustainable development of the social economy (Wang et al., 2022).

However, due to the huge uncertainties and lag effects of innovation as well as the lack of awareness of innovation responsibility in some enterprises (Gauttier et al., 2017; Jakobsen et al., 2019; Magni et al., 2022), entrepreneurs or Top Management Teams (TMT) tend to have a short-sighted view about corporate innovation behaviors. Thus, it is of great importance to study the issue, which is how to drive environmental protection enterprises implementing corporate responsible innovation (CRI) or under which circumstances do the enterprise will carry out responsible innovation behaviors.

Existing research has explored to some extent the target characteristics, ethics of responsibility, and implementation methods of responsible innovation (Saille, 2013; Burget et al., 2017), defining the basic elements of responsible innovation (including a broad interactive process of subjects, forward-looking forecasting, and the highlighting of moral factors), but findings on responsible industry projects suggest that firms lack the understanding of responsible innovation concepts (Gauttier et al., 2017; Stahl et al., 2019). At the same time, the behavioral logic of companies has shifted from a single point of departure of economic rationality to a focus on institutional rationality, and with it a shift in management perspective from a focus on efficiency only to a focus on organizational legitimacy (He et al., 2012). In other words, the behavioral logic (economic rationality, institutional rationality, social rationality, etc.) and management perspective (efficiency, effectiveness, legitimacy, etc.) of companies have become more diverse. Therefore, a comprehensive understanding of the factors influencing innovation behavior from the perspective of internal and external drivers is necessary to achieve a win-win situation in terms of both internal and external benefits. However, existing studies have started from a single perspective (internal or external) of what drives responsible innovation, focusing on the external (major social challenges (Chatfield et al., 2017a; Čeičytė, 2019; Schönherr et al., 2020), stakeholder (Auer and Jarmai, 2018; Tian and Tian, 2021) and internal [profit-seeking and risk reduction (Chatfield et al., 2017a), cultural values and institutional structures (Chatfield et al., 2017b; Ranabahu, 2020)] perspectives to explore the drivers of firms' implementation of responsible innovation, but there is a lack of research that

examines the role of corporate responsible innovation from an integrated internal and external perspective.

Some companies may not be sufficiently aware of their responsibility to innovate, which is likely to lead to a certain degree of short-sightedness in the innovative behavior of companies (Gauttier et al., 2017; Ranabahu, 2020), and thus there may be some real potential crises. From an external corporate perspective, companies may face increasing development pressure from competitors, pressure from social third-party agencies to evaluate, and pressure from consumers for high comfort and environmental protection (Power, 2008). Internally, companies need to maintain relationships with key stakeholders (e.g., high-end customers, government), comply with ethical regulations for energy efficiency and environmental protection, as well as follow their own strategic guidelines for product development, and avoid possible leakage of customer privacy information due to intellectual technology (Eden et al., 2013). These compounding realities, both internal and external, are partly driving companies to seek new management paradigms and concepts. In addition, the social consequences of technological innovation often lag behind, taking more than a decade to become apparent (Owen and Goldberg, 2010; Chatterjee et al., 2021). Therefore, the existing strategic thinking and governance paradigm of companies may not be able to address the negative externalities (e.g., data leakage) and lags of technology innovation, and there is an urgent need for innovative management models in the early stages of research and development, such as implementing corporate responsibility innovation to more effectively meet social needs and ethical constraints (Van den Hoven, 2013), so that companies can better deal with the potential crisis of ethics, environmental protection and sustainable development brought by technological innovation.

To sum up, we put forward the practical problems of implementing responsible innovation in companies and make contributions to the gradually expanding research literature on responsible innovation through the following analysis: (a) Clarifying the concept of corporate responsible innovation; (b) Exploring the internal and external mechanisms driving corporate responsible innovation in environmental protection enterprises.

The contribution of this study is mainly reflected in the following three aspects. Firstly, environmental protection enterprises are selected as the research objects, which expands the existing research scope of corporate responsible innovation. At present, research on corporate responsible innovation is concentrated in the fields of artificial intelligence, gene editing, nanomaterials, and biomedical ethics (Alexander and Katharina, 2017; Shelley et al., 2018; Bruce and Bruce, 2019; Buhmann and Fieseler, 2021). However, researches on industries closely related to the ecological environment such as environmental protection enterprises are scarce. Secondly, this study clarifies the concept

and structural system of responsible innovation at the firm level and enriches the scope of responsible innovation research. Previous research on responsible innovation has mainly focused on the macro level such as public governance, but less research has been conducted on the micro firm level. Thirdly, this study advances the study of the antecedents of corporate responsible innovation by exploring the drivers of corporate responsible innovation from both internal and external perspectives. By analyzing the internal and external environmental factors as a whole, the study facilitates a comprehensive understanding of the drivers of corporate responsible innovation.

The subsequent sections of this paper are organized as follows: the next section will review the literature on responsible innovation and corporate responsible innovation, as well as CRI's drive factors. This is followed by the description of the research methodology in Section 3. Section 4 will present the results, while the research findings will be discussed in Section 5, including the theoretical and practical contributions of this paper as well as an explanation of future research directions. This is followed in the sixth section by a summary.

2 Literature review

2.1 Responsible innovation

Starting from the research focus, the conceptual content of responsible innovation can be divided into three aspects: intrinsic attributes, process and management, and evaluation of results. Firstly, based on the internal attribute perspective of responsible innovation. Dreyer et al. (2020) emphasize that responsible innovation needs to be rooted in an innovation ecosystem of stakeholders, including government, business, and consumers, where each stakeholder has a role and responsibility, and where stakeholders are able to make forward-looking collaborative decisions based on existing knowledge to guide innovation in the direction of social needs satisfaction and ethical requirements (Stilgoe et al., 2013; Mei and Chen, 2015). Wilford (2016) focuses on the central role of the responsibility attribute of actors in the research and innovation process, arguing that responsible innovation creates a change whereby actors need to be concerned with the potential impact of their own practice of innovation and take responsibility for it.

Secondly, based on the process and management perspective. Schomberg (2012) proposes that responsible innovation is a transparent and interactive process in which social actors and innovators give feedback to each other, taking full account of the ethical acceptability, sustainability, and social desirability of the innovation process and its market products so that scientific and technological developments are properly embedded in social development. Stilgoe et al. (2013) then propose a broader definition of responsible innovation than the above, namely

that responsible innovation means exploring the future of innovation through the collective management of current science and innovation. Mei and Chen (2015) believe that responsible innovation is a dynamic process involving collaborative decision-making involving multiple stakeholders, which prospectively evaluates innovation objectives and results based on existing knowledge and builds an adaptive institutional system of science and technology governance to guide innovation toward the direction of social demands and moral and ethical requirements.

Thirdly, based on the evaluation of the results perspective. Hellström (2003) was the first to propose a framework for responsible innovation from a technology assessment and risk management perspective by analyzing forms of systemic innovation and their associated risks, through which the complex technical and risk issues of systemic innovation can be assessed and managed. Spruit et al. (2016) propose that responsible innovation is a collective collaborative and inclusive process to realize the transfer from the expected goal evaluation of the innovation process to the quality evaluation of the innovation process.

To sum up, the research on concept of responsible innovation are summarized in Table 1.

In the latest research on responsible innovation, the study of Kuzma (2022) shows that the main forces that hinder the implementation of responsible innovation in the governance system of emerging technologies are concentrated in the mesolevel and macro level, and uses the policy process theory to analyze the possible ways to bring responsible innovation into the national policy agenda. Ambos and Tatarinov, (2022) point out that responsible innovation wants a wide range of stakeholders to participate in scientific decision-making by expressing their needs and concerns, whereas individuals who believe in scientific conspiracies pose a challenge. Therefore, Popa and Blok, (2022) use the ideal experimental method to explore the relationship between responsible innovation and scientific conspiracy theories, and test four possible exclusion criteria for scientific conspiracy theories.

2.2 Corporate responsible innovation

Existing research on responsible innovation has focused on exploring the sources of ideas and the policy orientation of science and technology, in the public sector (Van den Hoven et al., 2012; Stilgoe et al., 2013; Pelle and Reber, 2015) and academic research (Van der Burg and Swierstra, 2013) predominantly, but there is little research on responsible innovation in business contexts (Pavie et al., 2014; Scholten and Blok, 2015; Foley et al., 2016), lacking exploration of the theoretical and practical implications of their management (Ribeiro et al., 2017). However, as the main body of innovation, the theoretical research on responsible innovation

TABLE 1 The research on concept of responsible innovation.

Research perspectives	Main research contents
The internal attribute perspective	- Responsible innovation needs to be rooted in an innovation ecosystem of stakeholders, including government, businesses, and consumers Dreyer et al. (2020) - Responsible innovation creates a change whereby actors need to be concerned with the potential impact of their own practice of innovation and take responsibility for it Wilford, (2016) - Responsible innovation requires stakeholders are able to make forward-looking collaborative decisions based on existing knowledge to guide innovation in the direction of social needs satisfaction and ethical requirements Stilgoe et al. (2013); Mei and Chen, (2015)
The process and management perspective	- Responsible innovation is a transparent and interactive process Schomberg, (2012) - Responsible innovation means exploring the future of innovation through the collective management of current science and innovation Stilgoe et al. (2013) - Responsible innovation is a dynamic process involving collaborative decision-making involving multiple stakeholders Mei and Chen, (2015)
The evaluation of the results perspective	Hellström, (2003) was the first to propose a framework for responsible innovation from a technology assessment and risk management perspective - Responsible innovation is a collective collaborative and inclusive process to realize the transfer from the expected goal evaluation of the innovation process to the quality evaluation of the innovation process Spruit et al. (2016)

of enterprises is of great significance. Since 2017, the research on responsible innovation has entered the exploration stage of theoretical construction, and the implementation and research of corporate responsible innovation have been paid more attention.

2.2.1 Implementation status: Exploration of responsible innovation in the business context

The exploration of responsible innovation in the business environment is in its infancy, and studies have been conducted to investigate successful practices related to responsible innovation in firms and to develop elements of evaluation indicators.

Findings regarding responsible industry projects suggest that firms lack an understanding of the concept of responsible innovation. However, this does not necessarily mean that they innovate in an irresponsible way ([Gurzawska et al., 2015](#)). For example, [Stahl et al. \(2019\)](#) through a qualitative survey of a number of companies in the ICT industry conducting 'responsible' activities, suggest that although they do not fully understand the meaning of responsible innovation, they are aware of some ethical and social issues related to their activities and have adopted some of the ideas of responsible innovation ([Stahl et al., 2019](#)). The results indicated that these companies, although not fully understanding the meaning of responsible innovation, were aware of some ethical and social issues related to their activities and had adopted some of the ideas of responsible innovation. However, in practice, the implementation methods to promote responsible innovation are often fragmented and not systematically integrated and effectively explored ([van de Poel, 2020](#)). Through business network resilience, [Xie et al. \(2022\)](#) found that responsible innovation has a positive impact on the sustainable

performance of enterprises, and the resilience of business networks plays a mediating role in this relationship.

Further, [Stahl et al. \(2017\)](#) constructed a maturity model for responsible research and innovation. Firms can assess their maturity level of responsible research and innovation in terms of purpose, process and product, and locate the stage of maturity they are at. [Jin et al. \(2016\)](#) constructed an index system for evaluating responsible innovation based on the need to evaluate responsible innovation in three aspects: the enterprise product design concept, the product production process and the evaluation and supervision mechanism in Dalian High-tech Zone, China. [Coffay et al. \(2022\)](#) put forward the comprehensive concept of responsible innovation laboratory, developed responsible innovation tools and impact tools, and developed environment-specific methods to predict and evaluate the potential of new enterprises to improve sustainability.

2.2.2 The conceptual content of corporate responsible innovation

At present, an academic exploration of responsible innovation concept in business focuses on managers' willingness to act and stakeholders' influence in the business environment. [Ramadhan \(2017\)](#) studied the individual behavior of responsible innovation in the business environment and argued that responsible innovation behavior refers to embedding the concept of responsibility into the beliefs, attitudes and intentions of individual innovators, i.e. adding responsibility to the whole process of innovation thinking, and eight questions were designed to measure four aspects of responsible idea generation, responsible fluency, responsible flexibility and responsible innovation realization ([Ramadhan, 2017](#)). [Čeičytė \(2019\)](#) identifies the main characteristics and

concepts of responsible innovation in business contexts based on literature analysis, arguing that responsible innovation is a democratic, inclusive and transparent innovation process that is used by organizations in solving major challenges related to related problems, seeking innovations with stakeholders that have positive added value for society and the environment, and using 11 items to measure responsible innovation behavior in companies (Čeičytė, 2019). Adomako and Tran (2022) studied environmental cooperation, responsible innovation and enterprise performance, and found that stakeholder pressure positively regulates the impact of environmental cooperation on responsible innovation, and responsible innovation further regulates the relationship between environmental cooperation and enterprise performance (Adomako and Tran, 2022).

However, the current definition of corporate responsible innovation is not tailored to enterprises. For business-oriented enterprises, their responsible innovation should be rooted in the ecological environment they rely on (Long et al., 2020; Wiarda et al., 2021) and based on what enterprises are already doing (Katharina et al., 2020). Therefore, we believe that corporate responsible innovation is inevitably embedded in the network of social development. Through openness, transparency and interaction, entrepreneurs or managers and other stakeholders urge enterprises to determine the current innovation behavior in order to prevent possible adverse results in the future, so as to take responsibility for innovation, that is, corporate responsible innovation is the responsible innovation behavior of enterprises facing social expectations. Such behavior should fully consider the external environment represented by ethics, public values, technical characteristics, industrial chain, industrial culture, etc. And the internal elements represented by entrepreneurs.

2.3 Influence factors for CRI

2.3.1 Motivations for implementing corporate responsible innovation

Firstly, from an organizational change perspective, the fact that organizations face major challenges is an important driver for firms to implement responsible innovation. The level of environmental cooperation of enterprises will affect corporate responsible innovation (Adomako and Tran, 2022). The networked nature of the environment in which firms operate facilitates the implementation of their responsible innovation, i.e., the integration of internal and external stakeholders in the firm contributes to the emergence of responsible innovation ideas and their implementation in the firm to address and solve major societal challenges (Chatfield et al., 2017a; Schönherr et al., 2020). In turn, major social challenges (e.g., poverty, health and safety) are important drivers of technological innovation (Pandza and Ellwood, 2013).

Second, from an institutional theory perspective, gaining legitimacy is an important factor that drives firms to implement responsible innovation. Trittin-Ulbrich and Böckel (2022) took corporate digital responsibility as an example to study how entrepreneurs in different fields construct corporate digital responsibility, so as to legalize the commitment of enterprises to responsible digital innovation. Responsible behavior is seen as necessary for organizational success and survival, and firms implementing responsible innovation can both improve their corporate image and potentially enhance their competitive advantage and thus increase profits (Stahl et al., 2019). Furthermore, corporate responsible innovation behavior is a strategic response to external institutional pressures (both formal and informal) and reflects an organization's ability to adapt and choose its external environment (Mei and Chen, 2015). And soft law mechanisms can help overcome the limitations of hard law in the global governance of responsible innovation in multinational organizations (Voegtlin and Scherer, 2017). Third, the demands of stakeholders such as consumers and public forces (Auer and Jarmai, 2018) also drive the implementation of responsible innovation in firms, with customer satisfaction being a strong and attractive incentive for firms. Mainstreaming responsible innovation into existing funding schemes is therefore an important incentive for firms (Zwart et al., 2014), as is the perceived legitimacy of responsible innovation to attract investment.

Fourth, in terms of organizational development, the pursuit of profit and risk reduction are the primary factors for firms to engage in responsible innovation. The potential for greater economic benefits from effective stakeholder involvement in innovation is widely accepted and, as a result, some firms may engage in activities related to responsible innovation for purely pragmatic reasons to reduce economic risk and improve the acceptability of their products and services (Zwart et al., 2014).

Fifth, in terms of corporate culture, cultural values and institutional structures have a profound impact on the development of responsible innovation. Corporate culture, awareness of responsible innovation, and ethical codes of conduct are important influences on the development of responsible innovation in firms (Chatfield et al., 2017b), such as implicit and explicit ethical commitments (Stahl et al., 2019), the intrinsic motivations of key individuals in the firm such as founders and executives, their attitudes towards responsible performance and their past experiences. In addition, the management and organizational structure of a company can promote responsible innovation by explicitly considering ethical, social or other responsibilities for action, and by supporting employees' commitment to implementing responsible innovation, which in turn facilitates its implementation.

In addition, some scholars have researched and proposed a more comprehensive set of drivers for responsible corporate innovation. On the one hand, instrumental motives (e.g.,

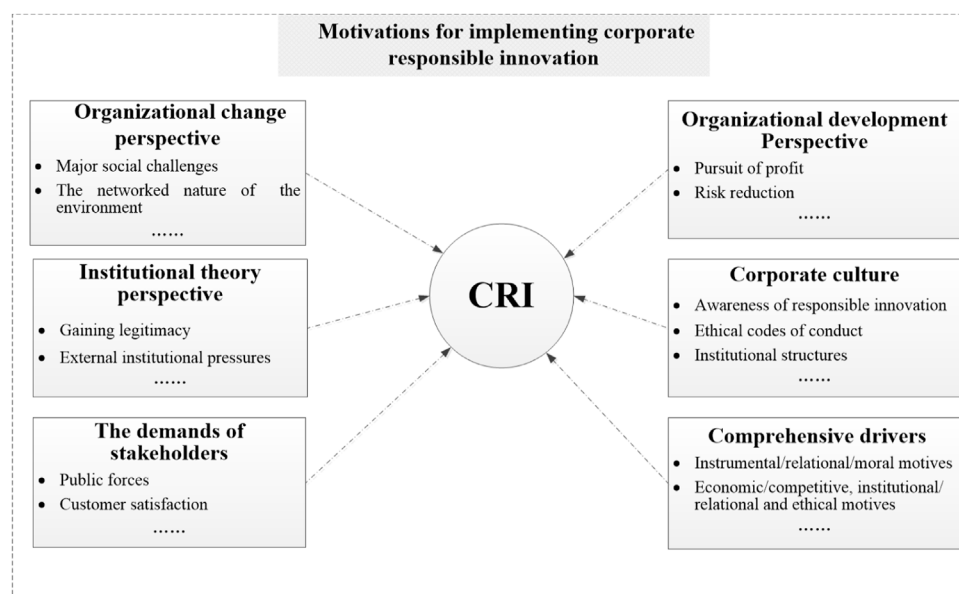


FIGURE 1
Motivations for implementing corporate responsible innovation.

profit-seeking), relational motives (e.g., voluntary compliance with laws and regulations under regulatory pressure, legitimacy craving) and moral motives (originating from companies and employee groups with high demands for moral and ethical norms) (Yaghmaei and Poel, 2021), or economic/competitive, institutional/relational and ethical motives (Chatfield et al., 2017b) are three important motivators that lead organizations to implement responsible innovation. On the other hand, the six factors, including regulatory framework, availability of financial resources, market orientation, customer knowledge, organizational structure and knowledge among innovation partners, will affect the degree of responsible innovation (Auer and Jarmai, 2018).

To sum up, the existing research about the motivations for implementing corporate responsible innovation are summarized in Figure 1.

2.3.2 Barriers for implementing corporate responsible innovation

Firstly, profitability is the primary consideration in business decisions, and this conflicts with the notion that responsible innovation goes beyond a financial profit-only orientation (Brand and Blok, 2019). Secondly, the prevailing notion of innovation, that it stems from information asymmetries in the marketplace and that firms have a clear incentive not to engage with stakeholders, is inconsistent with the openness and inclusiveness required by responsible innovation and may also lead to resistance from firms

(Garst et al., 2017). In addition, insufficient resources can limit the implementation of responsible innovation in firms, such as internal factors like budgetary constraints and funding issues, lack of human resources, and external factors like lack of financial support and investor understanding for responsible innovation in the market. Further, insufficient ethical considerations in organizations and systems are also important reasons why some people and institutions engage in irresponsible innovation behavior (Liu et al., 2016). Figure 2 presents the study of barriers factors for implementing corporate responsible innovation.

2.3.3 Situational factors for implementing corporate responsible innovation

Corporate responsible innovation may be associated with specific industries (Stahl et al., 2017), and therefore the industry in which a firm operates may be an important moderating variable. For example, in the context of ICTs for health, population change and wellbeing, many innovation processes are highly regulated and require close alignment with the values of responsible innovation (Chatfield et al., 2017a). Furthermore, Auer and Jarmai (2018) note that all factors can be drivers or barriers for firms to undertake responsible innovation, in the process of driving or hindering enterprises to carry out responsible innovation, many environmental or situational factors from inside (e.g., corporate culture) or outside (e.g., public policy) will have different degrees of influence in this process.

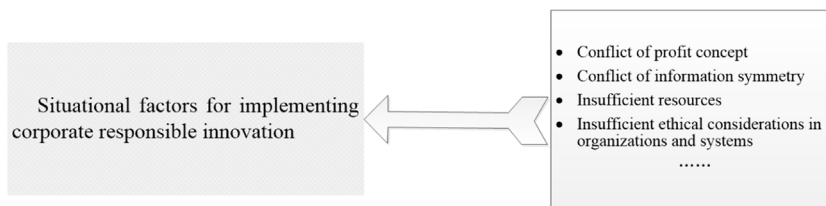


FIGURE 2
Barriers for implementing corporate responsible innovation.

2.4 Research on CRI based on internal and external perspectives of the organization

In the study of the drivers of corporate implementation of responsible innovation, scholars have generally adopted a perspective based on both external and internal organizational perspectives to explore. Because corporate responsible innovation requires the collaborative participation of multiple actors, the introduction of influencing factors from internal and external the organization and the refinement of the roles, functions and division of labour of different actors are more conducive to a comprehensive understanding of corporate responsible innovation. For example, Chatfield et al. (2017a) et al. explored the drivers of implementing responsible innovation in ICT firms from the perspective of both external to the organization (significant social challenges) and internal to the organization (pursuit of profit and risk reduction) (Chatfield et al., 2017a). Cao and Chen, (2017) et al. explored the driving effects of external policy pressure, market pressure, internal innovation resources, and innovation capabilities on green innovation strategies from an internal and external environmental perspective, using 216 firms as a research sample (Cao and Chen, 2017). In addition, van de Poel (2020) discusses how companies can integrate responsible research and innovation into their socially responsible policies and business strategies (van de Poel, 2020). The impact of the internal and external environment on a firm's responsible research and innovation strategy is explored at both the strategic and operational levels, and Key Performance Indicators (KPIs) for corporate responsible research and innovation are developed to help firms measure the extent of implementation and outcomes of responsible innovation. Therefore, it is feasible and important to study corporate responsible innovation from a dual perspective of internal and external organization.

2.5 Environmental protection enterprises and CRI

The environmental protection enterprises in our study include those engaged in water pollution control, air pollution control, noise control, and solid waste treatment et al. The

innovation-driven development of environmental protection enterprises is characterized by the allocation of relevant human resources, financial resources and capital, as well as the conversion efficiency of resource value and patent output (Bărbulescu et al., 2021). The prospect of responsible innovation is to achieve sustainable economic and social development. The existing research results show the innovative companies are always sustainable, there is a positive correlation between innovation and enterprise sustainability (Sempereripoll et al., 2020). The environmental protection industry is one of the most complex industries. Due to various challenges in project planning and research, great efforts are required. In recent years, the construction of the environmental protection industry has been promoted to the top of national strategy in China (Feng et al., 2022). Therefore, it is of great significance to study the responsible innovation of environmental protection enterprises.

In summary, firstly, there is still a lack of sufficient integration between responsible innovation and business in terms of practical application (Schönherr et al., 2020). Although some scholars have investigated companies conducting 'responsible' activities and attempted to construct a system of indicators for evaluating responsible innovation in companies, a maturity model, and key performance indicators to measure the level of implementation of responsible innovation, the evaluation methods are mainly qualitative analysis and fragmented descriptions. The difficulty in effectively screening and objectively evaluating the level of implementation of corporate responsible innovation is an important reason for the slow promotion of the concept of responsible innovation at the enterprise level. As an innovation subject, enterprises run through the research and practice of responsible innovation from stakeholders to important participants, then to key implementation subjects, and from "behind the scenes" to "in front of the stage", playing a more and more obvious role. Therefore, it is urgent to focus on the research of corporate responsible innovation.

Second, previous studies have analyzed the influencing factors of corporate responsible innovation from the aspects of environmental networks and major challenges (Čeičytė, 2019), legitimacy acquisition (Stahl et al., 2019), institutional

pressures (Mei and Chen, 2015; Voegtlin and Scherer, 2017), stakeholder requirements (Ramadhan, 2017), and corporate culture (Chatfield et al., 2017b), but as they are developed separately and not systematically integrated, it is also difficult to comprehensively consider the joint influence of multiple internal and external factors and the interactions between different factors, making it difficult to carry out quantitative analysis and in-depth exploration of the driving mechanisms. The current study will explore the driving factors of responsible innovation from internal and external perspectives.

3 Methodology

Qualitative research can choose from a number of different forms of data collection, and we chose in-depth interviews as the most appropriate method for this study. Burgess, (1988) describes an interview as a type of “purposeful conversation”, and interviews are probably the most commonly used method of qualitative data collection. Compared to other methods such as questionnaires (Opie, 2004; Montazeri et al., 2016), interviews allow researchers to gain a deeper understanding of participants’ attitudes, beliefs and perceptions. In addition, the use of interviews is well suited to investigating topics for which data may not be available in other forms, those for which data may only be found among key informants or “key players in the field” (Denscombe, 1998). Interviews with these key figures can provide a direct route to in-depth information that is not available elsewhere.

The initial interview question was raised by the members of the research group in 2 months. The researchers asked 9 questions in an attempt to reveal respondents’ experiences and perspectives on the topic of CRI. Respondents were asked questions about their level of knowledge of CRI, existing practices, and motivations for implementing CRI (see Appendix A for details).

In summary, to facilitate an understanding of what CRI means for enterprises, we began with the following two research questions:

- What is the concept of current CRI-related activity?
- What are the potential drivers for CRI in environmental protection enterprises?

3.1 Data collection

This study’s consideration of Corporate Responsible Innovation arises under the influence of the negative externalities that exist in the development of science and technology innovation. Therefore, we conducted 13 in-depth interviews in some environmental protection enterprises in China. All interviewees are currently or have previously held

at least one key position in a large or small enterprise. To ensure anonymity, interviewees’ individual names and their companies could not be identified, Table 2 provides an anonymized overview of interviewer characteristics.

Interviewees receive an invitation letter and an information sheet. Each interview lasts approximately 45–120 min and is conducted *via* face-to-face or online voice communication. All interviews were conducted in an ethical manner, such as informed consent, respect for privacy, and avoidance of harm and deception (Diener and Crandall, 1978; Frey and Fontana, 2005). In addition, each subject member followed the same interview guidelines, which were developed specifically for this study, and used the same interview schedule. This was necessary to promote consistency among the interviewers.

Although semi-structured interviews use pre-set questions, the actual topic varies between participants to allow respondents to describe their personal experiences, opinions and feelings about the subject matter. The interviewer’s task is to ask for details or seek clarification if necessary, rather than to provide opinions or use leading questions. The interviews were conducted using recursive questioning so that they proceeded as a conversation rather than a question and answer session.

3.2 Data analysis

Following Chatfield et al. (2017b), the method we use is content theme analysis, as described by Burnard et al. (2008). This method is usually used for qualitative data analysis, including a detailed review of interview records to determine the themes and categories within the data. We invited three professional researchers to conduct manual step-by-step coding. By classifying and refining the contents of the interview manuscript, we improved the level of abstraction and interpretation and formed clear themes and categories.

First, all interview descriptions are screened according to the following two criteria: On the one hand, the description must have a clear meaning. On the other hand, the description must be related to CRI. Secondly, the purpose of data analysis is to extract themes from a large number of qualitative data. After further merging similar items, merging semantically similar descriptions, eliminating semantically ambiguous descriptions, and eliminating descriptions that do not match the reality of the company, a total of 20 items about corporate responsible innovation were obtained. Furthermore, after repeated deliberation by three professional researchers and further induction of all interview descriptions, 4 dimensions were obtained about the concept and behavior of corporate responsible innovation. Similarly, 6 dimensions about the driving factors of corporate responsible innovation in environmental protection enterprises were extracted.

TABLE 2 Anonymized overview of the interview participant details.

Code	Type of business	Size	Position held	Interview duration
1	Environmental technology services	Small	CEO	1 h
2	Sewage treatment	Small	CEO	0.8 h
3	Urban solid waste comprehensive services	Small	CEO	1 h
4	Solution for the urban waste treatment	Small	CEO	2 h
5	New energy technology	Small	CEO	1 h
6	Water pollution control	Large	Minister of government affairs	1.5 h
7	Air pollution control	Large	Head of R&D Department	1.5 h
8	Energy recovery system development	Large	Head of Business Department	1.5 h
9	Water conservancy project quality inspection	Small	CEO	1 h
10	Photovoltaic power	Large	CEO	1.5 h
11	Environmental protection monitoring	Small	Head of R&D Department	1 h
12	Noise control	Small	CEO	1.2 h
13	Environmental monitoring	Small	CEO	1.5 h

TABLE 3 Research questions and associated dimensions.

Research question	Dimensions/factors
What is the concept of current CRI-related activity?	Inclusion
	Anticipation
	Reflexivity
	Responsiveness
What are the potential drivers for CRI in environmental protection enterprises?	Market pressure
	Policy pressure
	Normative pressure
	Motivation of responsible innovation
	System of responsible innovation
	Elements of responsible innovation

4 Results

Table 3 details the two questions and their respective dimensions and factors that emerged from the subsequent analysis, showing the relationship between the research questions and the categories.

In the following content, these two research questions and their dimension classification will be explained in more detail, and each dimension is provided with explanatory quotes from respondents to help summarize its meaning. The interviews were coded (1–13), representing the serial number of the respondents respectively.

4.1 The concept of corporate responsible innovation

In the interviews, we asked respondents about their level of knowledge of CRI and four categories were extracted from the deep descriptions of the participants including “inclusion,” “anticipation,” “reflexivity,” and “responsiveness”.

4.1.1 Dimension 1: Inclusion

Corporate responsibility innovation is oriented towards inclusion, it is to induce more stakeholders to participate in innovation activities, which can be done through various ways

such as dialogue and debate for collective deliberation of innovation activities and listening to the demands of different subjects on innovation activities. All respondents, without exception, agreed on the need and benefits of stakeholder involvement in innovation activities, which is typical of the responses:

"When undertaking an innovative activity, the interests of all parties need to be weighed and considered." (1: Consider the interests of stakeholders)

"Balancing the interests of all parties: the customer is at the core, because he has to use your stuff and consume it through him. Second is all the employees of the company. The third is the company's shareholders." (4: Consider the interests of the stakeholders)

Integrating the interests of stakeholders in the innovation process is ultimately a win-win situation in order to achieve economic and social benefits, as the interviewees talked about in their interviews:

"People who come and refer business to me get a commission, and the commission from referring you by sharing the referral counts towards your earnings." (4: Win-Win with Stakeholders)

In addition to considering the interests of stakeholders and achieving a win-win situation with them, two other dimensions of inclusions were included in the interview themes: observing social and business ethics in the innovation process and considering the responsibility of innovation for ethical, ecological, economic and social development. As the interviewee said in the interview:

"We take the culture of mutual trust as the support of supply chain management, build and share the business atmosphere of integrity with the upstream and downstream supply chain nodal enterprises, and form a very competitive strategic alliance." (2: Observe social and business ethics)

"In terms of adopting green technologies, we focus on selecting recyclable, renewable, degradable and easy to treat green materials and cleaning equipment to achieve green supply chain management." (5: Consider the responsibility of ethical, ecological, economic and social development)

4.1.2 Dimension 2: Anticipation

Adverse impacts of new technologies are often not foreseen and risk-based hazard estimates often do not provide early warning of future impacts (Hoffmann-Riem and Wynne, 2002). Anticipation is to anticipate the potential impacts and risks directly related to the science and technology innovation

activities themselves and to effectively deal with the unintended consequences that may arise from research and innovation through technology assessment, scenario planning, and other methods (Bozeman et al., 2015; Kuzma and Cummings, 2021), taking into account social, environmental, and ethical influences, so as to "prospectively govern" the innovation activities and realize the controllable risks of innovation activities. The majority of interviewees indicated that they anticipate the ethical, ecological, economic, and social risks that innovation may pose:

"The environmental protection piece, we have brought in some advanced talents from the country and internationally. Before doing each project to start construction, our environmental protection department will assess environmental safety, which also includes part of social responsibility." (6: Forecasting risks)

"We ask for a lot of early warning before we do each project." (6: Predicting risk)

Forecasting is forward-looking systems thinking that situates innovation within the study of socially robust crisis management, thus placing the possibility of negative externalities, innovation uncertainty and other factors arising from scientific liberalism in the context of manageable social crisis management and social development orientation. For example, some interviewees mentioned that they consider the possible outcomes of innovation from a long-term perspective of social and environmental benefits:

"Any design we do is not only for the present but also for the future. We have to sink what remains the same to deal with what changes in the future, to respond quickly to what changes, to create productivity that can be replicated quickly." (7: Considering long-term outcomes)

"From a forecasting perspective, in the midst of the innovation process, predicting the future, the impact of this thing years down the line." (7: Considering long-term outcomes)

4.1.3 Dimension 3: Reflexivity

Responsibility requires reflection by actors on the known or unknown purposes, motivations and potential impacts of innovation (Stilgoe et al., 2013), which implies self-reflection on the assumed premises, requirements, goals, processes of implementation, and outcomes of innovative activities, and the realization that a particular framework for an issue may not be universally held. Social theorists consider reflection as a condition of contemporary modernity (Beck et al., 1994).

"When companies innovate, they must adhere to the relevant requirements of the overall regulatory policy, which is the red

line, what can and cannot be done, what is done by licensed institutions and what is done by non-licensed institutions, clearly delineated." (10: Reflection and Legitimacy)

Depending on the level of knowledge of CRI, respondents generally agreed that there is a need for reflection in the innovation process, particularly on the legality of innovation activities, i.e. thinking about whether innovation activities comply with laws and regulations. Respondents also talked about reflecting on other aspects, such as the importance of involving stakeholders in the evaluation of innovation activities and whether potential threats to innovation are regularly and openly discussed within the organization.

"We don't let people monitor the innovation process, but of course visiting sometimes does. When something goes wrong it will be adjusted in time, for example if I find out that the thing has had a negative effect, then I will also correct it in time." (1: Formal evaluation)

"Every month we have a full staff meeting with the leadership and CEO and then listen to what the staff thinks." (6: Open discussion of threats and limitations)

4.1.4 Dimension 4: Responsiveness

Responsiveness is about responding to new knowledge, perspectives, views, and normative norms. Specifically, responsiveness involves the establishment of an interactive, continuous, and flexible adaptive learning process through institutionalized interrogation mechanisms when knowledge and control over innovation are felt to be insufficient, the framework and direction of innovation activities are moderately adjusted, the human value system is incorporated into the research framework of responsible innovation in the technological design process, and the institutional coupling of the innovation evolution process responsive to social values is realized. Responsible innovation requires the ability to change form or direction in order to respond to stakeholders and public values as well as to changing circumstances. During the interviews, we learned that it is important to integrate key stakeholders into the innovation process:

"So-called responsible innovation actually starts by allowing the company to build up the kernel first, and then it naturally attracts wider public participation." (5: Integrating stakeholders into the innovation process)

"We got a big expert in the industry to collaborate, the technology he developed, and I provided the funding, the space, and the conditions for the facilities." (1: Integrating stakeholders into the innovation process)

In addition, maintaining close communication with stakeholders, such as the public and the organization's

employees, regarding the content of the innovation and adapting it to the important information provided by stakeholders are also important behavioral manifestations of responsible innovation:

"There will be public participation instructions on environmental protection, which is based on the public participation approach to environmental impact assessment, and online newspapers to collect public opinion; employees will also be informed at meetings and all-employee emails. There are too many people with too much information and one-to-one communication may not be possible, but the company will use all-employee emails or CEO meetings and departmental meetings to inform employees." (6: Transparency to stakeholders)

"For example, if I make this one good, but it has a negative impact on the next one, this is something we cannot allow to happen and go for a revision." (1: Adapting innovations to reflections)

We argue that the role of enterprises in responsible innovation research and practice gradually changes from combining corporate social responsibility with technological innovation to combining corporate open innovation with responsible ethics to combining corporate innovation governance with specific industries, and that corporate responsible innovation is embedded in a certain industrial environment and ethical social environment. Furthermore, the overall situation of the industry has a significant impact on corporate responsible innovation. By combining the specific characteristics of the industry in which the company is located, such as industrial technology and industrial chain, and by studying and judging the trends of technology risk, intellectual property rights, industrial layout, industrial agglomeration, industrial transformation and upgrading, corporate responsible innovation can be better implemented in the industrial innovation ecosystem in which the company is located (Stahl, 2022). As an important part of the national innovation system, enterprises need to comply with the requirements of morality, ethics, public values and social culture of the country they are located in to carry out innovation activities, and to build up responsible thinking, awareness and responsibility for innovation development from the bottom. On this basis, the connotation of corporate responsibility innovation can be elaborated through "one subject, one factor and four goals". In summary, the core connotations and structural dimensions of CRI are distilled through content analysis, and the preliminary connotation analysis is shown in Figure 3, and the complete 20 items and 4 dimensions are shown in Table 4.

1) Enterprise subject: the enterprise is the subject of implementing responsible innovation. Guided by inclusion, by involving stakeholders in innovation collaborative governance, conducting anticipation, reflexivity and

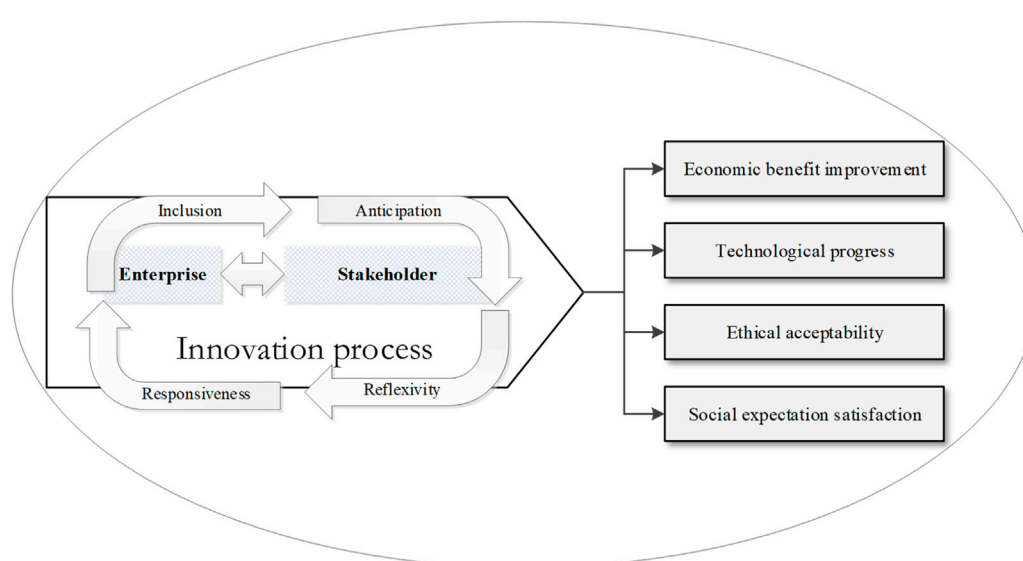


FIGURE 3
The concept map of corporate responsible innovation.

responsiveness in the process of idea formation, idea screening and idea verification implementation, and jointly seek innovation with stakeholders that have positive added value for society and the environment (Čeičytė, 2019).

- 2) Individual factor: whether and when enterprises implement responsible innovation, entrepreneurs play an irreplaceable role. Therefore, the concept of responsibility is embedded in the beliefs, attitudes and intentions of individual entrepreneurs, and responsible thinking is added to the realization of innovation (Ramadhan, 2017).
- 3) Four goals: on the basis of the existing technological innovation goals of “technological progress” and “economic benefit improvement”, responsible innovation requires that the results of innovation activities must meet “ethical acceptability” and “social expectation satisfaction” (Van den Hoven, 2013; Owen et al., 2012). The fundamental goal of innovation evaluation is to achieve public value.

4.2 Drivers of corporate responsible innovation

Considering the extra effort and resources that CRI requires from companies, in the interviews we asked respondents why they bothered to do this. Combining the interviews, the following six factors that drive companies to engage in responsible innovation have been summarised.

4.2.1 Driver 1: Market pressure

Responsible corporate innovation behavior is a strategic response to external market pressures and reflects a firm’s ability to adapt to the external environment, with firms engaging in responsible innovation-driven to some extent by the market. Respondents indicated that they engage in responsible innovation to a large extent from consumers, most of whom evaluate a company’s reputation based on whether it is responsible in its innovation process, as they believe that responsible innovation by firms can benefit society.

“Before making innovation decisions, we should put the needs of users in the first place. By meeting the growing healthy and positive needs of customers, we should combine innovation with social responsibility and give play to social value.” (5: Consumer pressure)

In addition to consumers evaluating the reputation of companies, some professional third-party organizations also monitor companies as they implement responsible innovation, for example by issuing appropriate reports to evaluate the responsibility of companies’ innovation, as interviewees said.

“Third party institutions will investigate our innovation process from time to time, and the results of the industry responsible innovation report at the end of each year are the wind vane for us to continue to implement corporate responsible innovation.” (9: Third party pressure)

TABLE 4 The items and dimensions of corporate responsibility innovation.

Items	Dimensions	Typical sentence from the interview
We will comprehensively consider the interests of stakeholders in the innovation process	Inclusion	<i>"When undertaking an innovative activity, the interests of all parties need to be weighed and considered."</i> (1: Consider the interests of stakeholders)
We pursue win-win results for enterprises and stakeholders in the process of innovation		
In the process of innovation, we regard compliance with social ethics and business ethics as our due social responsibility		<i>"People who come and refer business to me get a commission, and the commission from referring you by sharing the referral counts towards your earnings."</i> (4: Win-Win with Stakeholders)
We will consider the responsibility of innovation for ethical, ecological, economic and social development		
We consider the possible results of innovation from the long-term perspective of social and environmental benefits	Anticipation	<i>"We ask for a lot of early warning before we do each project."</i> (6: Predicting risk)
We evaluate the entire life cycle of innovation from a social and environmental perspective		
We have preset some possible scenarios for innovative development		<i>"From a forecasting perspective, in the midst of the innovation process, predicting the future, the impact of this thing years down the line."</i> (7: Considering long-term outcomes)
We predict the ethical, ecological, economic and social risks that innovation may bring		
Compared with our peers, we are more concerned about whether innovation complies with relevant regulations	Reflexivity	<i>"We don't let people monitor the innovation process, but of course visiting sometimes does. When something goes wrong it will be adjusted in time, for example if I find out that the thing has had a negative effect, then I will also correct it in time."</i> (1: Formal evaluation)
We will reflect on the impact of innovation on ethics, ecology, economy and society		<i>"Every month we have a full staff meeting with the leadership and CEO and then listen to what the staff thinks."</i> (6: Open discussion of threats and limitations)
Compared with our peers, we pay more attention to involving stakeholders in the evaluation of innovation activities		
We openly discuss the potential threats and limitations of innovation within the organization		
We are transparent in assessing the potential risks of innovation		
In order to achieve social and environmental benefits from innovation, we coordinate incompatible values among stakeholders		
Compared with our peers, we pay more attention to the introduction of third-party evaluation and certification in the innovation process		
We integrate key stakeholders into the innovation process	Responsiveness	<i>"We got a big expert in the industry to collaborate, the technology he developed, and I provided the funding, the space, and the conditions for the facilities."</i> (1: Integrating stakeholders into the innovation process)
We maintain close communication with stakeholders in terms of innovative content		<i>"For example, if I make this one good, but it has a negative impact on the next one, this is something we cannot allow to happen and go for a revision."</i> (1: Adapting innovations to reflections)
We adjust the innovation content according to the important information provided by stakeholders to obtain economic and social benefits		
In the process of innovation, we feed back the implementation of their suggestions to stakeholders		
In response to emergencies in innovation activities, we have paid more attention to safeguarding social benefits		

Pressure from suppliers is also an important driver of responsible innovation in companies. In their business dealings, suppliers make judgements about whether the innovation process is

responsible for the enterprise and thus derive an assessment of the enterprise, particularly those suppliers who have launched socially and environmentally friendly products.

"Now the environmental protection requirements are getting higher and higher. We need to develop new materials to solve the original environmental pollution problem, and the threshold set by suppliers in environmental protection is also getting higher and higher." (1: Supplier pressure)

In addition, in a highly competitive market environment, modern firms operate with a strong focus on the ethics and morality of innovation, particularly as the high level of interest from peer competitors in undertaking responsible innovation can drive firms to implement responsible innovation.

"We are not willing to do the traditional model. We should solve the pain points of the industry and enter the blue ocean market through responsible innovation." (1: Competitor pressure)

4.2.2 Policy pressure

With the continuous improvement of various national laws, regulations and policy systems related to entrepreneurship, higher requirements are placed on the innovative activities of enterprises. In this context, the mandatory policy is reflected in the fact that if a company harms the interests of society and violates morality and ethics in its innovation activities, then it will be severely punished. As interviewees talk about:

"Actually, at the moment, doing responsible innovation is due to legal pressure, meaning that the state requires us to do it, and then we have to do it." (4: Legal red lines)

"A basic starting point is surely to comply with the law." (8: Legal red lines)

In fact, the implementation of responsible innovation by enterprises is not only due to the pressure of laws and regulations, but also due to the local government's efforts to improve the relevant laws and regulations, the formulation of tax incentives, the provision of special financial subsidies and preferential loans.

"Today we see the State Council's heavy innovation stuff, how about a registration system, how about companies filing for assets, a corporate bankruptcy system coming out, and personal bankruptcy laws coming out. We can then feel comfortable with responsible innovation and can let go of the need to contribute to society. The protection of the law actually breaks the stranglehold of innovation." (3: Policy: Positive)

4.2.3 Normative pressure

Corporate responsible innovation can be influenced by the overall national and sociocultural environment. As interviewees talked about:

"Innovation brought about by the general environment of social progress will affect the responsibility of the innovation process. When innovation improves the overall efficiency of society and loses the interests of a small number of people, we will also carry out responsible innovation." (3: Normative pressure)

"Through the advocacy of responsible innovation values, the public's level of innovation awareness has reached a higher level." (7: Normative pressure)

"For example, the COVID-19 epidemic has accelerated our digital transformation." (7: Normative pressure)

If the state promotes the idea of socially responsible innovation, strongly encourages responsible stakeholder behavior when innovating, and the company's leaders and employees are happy to be educated about the responsibility of innovation, then the company will to a large extent implement the behavior of responsible innovation. This is influenced by normative pressures, i.e. shared concepts and norms of meaning developed in national and regional cultures, values, normative beliefs and behavioral assumptions, which are agreed, assessable as well as obligatory dimensions of social life.

4.2.4 Motivation of responsible innovation

Innovative activities by companies help to continuously expand profitability channels and business scale and enhance the profitability of existing businesses. Clear economic benefits are therefore the main driver for corporate responsible innovation.

"Innovators think about whether I can win the market using this big data and are profit-oriented. When companies go to make decisions, they must be profit-oriented, I'll do it as long as I don't break the law and there's money to be made." (3: instrumental motivation)

In considering economic efficiency, companies also focus on and maintain relationships with core stakeholders, such as customers, peers and suppliers, and establish or maintain win-win relationships with them through innovation.

"The primary task of our innovation is to meet the market demand and solve the pain points of the industry, which is also a reflection of our responsibility. We have established long-term cooperative relations with some customers and suppliers." (1: Relationship motivation)

Interaction with society and the public will also drive enterprises to carry out responsible innovation. Corporate responsible innovation itself is guided by inclusion, as the interviewer said:

"Products made through innovation respond to everyone's concerns, and the public continues to accept, participate and experience. It is not enough to rely on our own enterprise. To be exact, it is everyone who works together to develop the industry." (6: Moral motivation)

4.2.5 System of responsible innovation

A company undertaking responsible innovation will have its own innovation strategy, such as a dedicated person responsible for the socially responsible management of the innovation project, training to carry out the innovation project, or a clear reward or evaluation system for the company to carry out the innovation project responsibly, as in this typical interview dialogue.

"Our company is very open in the internal management of employees. We encourage the implementation of the job rotation system, carry out regular training, and publicize responsibility innovation projects." (6: System of innovation)

These innovation systems underpin corporate responsible innovation and are an important driver of responsible corporate innovation.

4.2.6 Elements of responsible innovation

Another driver frequently mentioned in the interviews was the conditions for innovation in the firm. Among these, innovation resources are important for corporate responsible innovation, with higher investment in research and a high level of technological equipment compared to other companies in the same sector being important drivers of responsible innovation.

"Increasing investment in science and technology is one of the prerequisites for responsible innovation." (6: Innovation resources)

In addition, companies with human resources of a high scientific quality are usually able to complete innovative projects with high quality, as this interviewer said.

"We have introduced top talents from all over the world, established the top water pollution control team, and brought new technologies and new management concepts." (6: Innovation resources)

In addition to innovation resources, a firm's own ability to innovate is an important driver. For example, the originality of a product, the number of patents filed, and the speed and success of new product development can have an impact on whether a firm engages in responsible innovation.

"Our next step is to strengthen the research and development speed of this batch of environmental protection materials,

which will have a great impact on our responsible innovation." (1: Innovation ability)

Motivation is the cause and motivation that triggers behavior, and the transformation of organizational motivation into organizational behavior requires a weighted consideration of situational factors (Grewal et al., 2001; Liu et al., 2016). Therefore, based on the model of "moral factors affecting behavior" (Weber, 1990; Trevino et al., 2006), we propose a framework of drivers of corporate responsible innovation with the responsible innovation motivations as the core trigger variables, responsible innovation elements and responsible innovation system as the internal organizational factors, and market pressure, policy pressure and normative pressure as the external organizational factors in Figure 4.

5 Discussion

We clarified the concept of corporate responsibility innovation through interviews with 13 corporate executives and summarized a four-dimensional framework for corporate responsibility innovation: Inclusion, anticipation, reflexivity, and responsiveness. In addition, we propose an MPN-MSE model of the drivers of corporate responsibility innovation in environmental protection enterprises from the perspective of external organizations [including Market Pressure (M), Policy Pressure (P) and Normative Pressure (N)] and internal organizations [including Motivation of responsible Innovation (M), System of responsible innovation (S) and Elements of responsible innovation (E)]. The theoretical and practical significance of this study is discussed below.

5.1 Theoretical implications

Firstly, environmental protection enterprises are selected as the research objects, which expands the research scope of corporate responsible innovation. Under the impact of the tide of environmental protection in the world today, all countries attach great importance to the high-tech research of protecting the environment, saving resources and energy. For environmental protection enterprises, it is incumbent on them to carry out responsible innovation as they are closely related to people's livelihood. Our research explores the concept of corporate responsible innovation and the factors that drive technology environmental protection enterprises to carry out responsible innovation, which enriches the scope of research objects of corporate responsible innovation.

Secondly, this study further clarifies the concept and structural system of responsible innovation at the firm level and enriches the relevant research on responsible innovation. On the one hand, although scholars have explored the concept

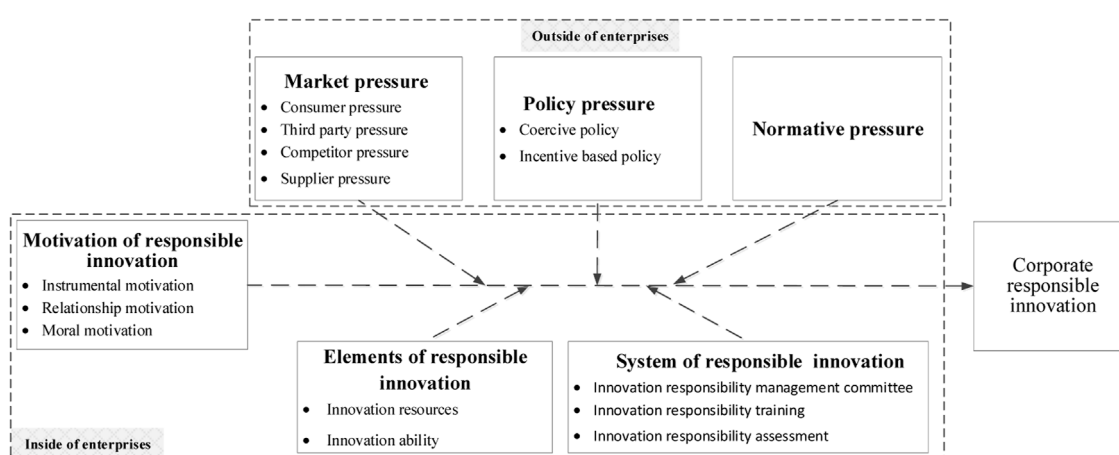


FIGURE 4
Drivers of corporate responsible innovation.

and connotation of responsible innovation to some extent, such as the target characteristics of responsible innovation, ethics of responsibility, and implementation methods, and defined the basic elements of responsible innovation, including the extensive interactive process of subjects, forward-looking forecasting, and the highlighting of ethical and moral factors (Saille, 2013; Burget et al., 2017), the core characteristics, key aspects, defining criteria and assessment guidelines of responsible innovation are still not clear. On the other hand, responsible innovation has received widespread attention from the public sector, but companies, as innovation agents, do not have sufficient awareness and recognition of responsible innovation. Theoretical and practical exploration of responsible innovation in the business context is still in its infancy. We summarize the orientation, innovation process, results and essence of corporate responsible innovation through interviews, and propose four structural dimensions of corporate responsible innovation: inclusion, anticipation, reflexivity and responsiveness, promoting the conceptual study of corporate responsible innovation. Besides, previous scholars have proposed the AIRR framework (anticipation, inclusiveness, reflexivity, and responsiveness) for responsible innovation (Ranabahu, 2020). However, the AIRR framework has not yet indicated the specific subjects to which it can be applied. We further develop the framework by applying it to corporate responsible innovation and validating it through interviews.

Thirdly, this study explores the drivers of corporate responsible innovation from both internal and external organizational perspectives, enriching the antecedents of corporate responsible innovation. Although a few scholars have initially explored the organizational practice of responsible innovation and analyzed the factors influencing responsible innovation from different perspectives, they have

done so separately and not systematically, making it difficult to consider the joint influence of multiple factors and the interactions between different factors. Moreover, current research is limited to the conceptual integration of related theories and the construction of alternative management frameworks, such as debates on the concepts of corporate social innovation (Sliva, 2017), suggesting that the five-stage corporate citizenship theory in CSR can be used as a theoretical framework for responsible innovation (Hemphill, 2016), there is a lack of exploration of the foundations and motivations for the micro-implementation of responsible innovation. Firms engaging in responsible innovation are driven by external pressures on the one hand but also influenced by the internal environment of the firm on the other. This paper proposes the MPN-MSE model through a holistic analysis of internal and external organizational environmental factors, which is conducive to a comprehensive understanding of the drivers of corporate responsible innovation.

5.2 Practical implications

Firstly, for entrepreneurs, the results of a conceptual study of corporate responsible innovation help to increase the level of awareness and importance of responsible innovation among entrepreneurs and improve the effectiveness of corporate responsible corporate innovation practices. Although research suggests that firms may not necessarily innovate in an irresponsible manner, the current awareness and recognition of responsible innovation among firms is low (Hemphill, 2016; Jin et al., 2016; Stahl et al., 2019), resulting in a significant reduction in the effectiveness of responsible innovation practices. The results of this study clarify the core

connotations and structural dimensions of corporate responsible innovation, guide entrepreneurs to grasp the correct responsible entrepreneurial orientation and transfer the concept and awareness of responsible innovation to their employees, integrate core stakeholders into the whole innovation process, and achieve technological progress and economic benefits under the premise of being ethical and achieving social satisfaction.

Secondly, for environmental protection enterprises, this study shows that innovation motivation, innovation systems and innovation conditions are the internal drivers of responsible innovation. On the one hand, organizations often influence the behavior of employees and firms through the adjustment of their internal environmental protection systems, which are important for the operation of firms, and can gain competitive advantages for firms through the management and planning of their internal system structure. Therefore, enterprises should establish a sound internal environmental innovation system, i.e., make relevant regulations on the issue of responsibility in the management system of innovation, and coordinate the interests between the company and its stakeholders through a set of formal or informal systems or mechanisms to safeguard the interests of all aspects of the company. On the other hand, increase the investment in capital, technology, human resources and other resources for environmental innovation, improve the ability to effectively obtain information, integrate resources, absorb knowledge and apply it to innovation activities, and create conditions for responsible innovation.

Thirdly, for governments, the research shows that market pressure, policy pressure and normative pressure are external drivers of corporate responsible innovation. All three of these drivers are influenced by local government regulation, which provides practical guidance on how governments can drive firms to implement responsible innovation. In general, governments influence firms' strategic choices by setting and enforcing regulations. For governments, on the one hand, need to design a set of incentives/constraints to drive firms to implement responsible innovation. On the other hand, since customers are an important incentive for firms to innovate responsibly (Schönherr et al., 2020), and they influence corporate responsible innovation through product choice, governments also need to guide their customers to actively participate in responsible innovation.

5.3 Limitations and future direct

Despite the theoretical and practical implications of this paper, we acknowledge certain limitations in our research but believe these could pave the way for future research avenues.

Firstly, our qualitative study of 13 samples was limited and inevitably subjective. Although proactive measures were taken to minimize subjective bias on the part of the researcher and

respondents during the interview process, data collection and analysis, it must be acknowledged that in qualitative research, the findings are 'co-created' by the people involved, a degree of bias is inevitable (Denzin and Lincoln, 2011). In the future, the generality of the results need more examinations, a combination of qualitative and quantitative research can be used to develop a measurement scale for responsible corporate innovation by combining qualitative and quantitative research, summarising initial questions through a qualitative research process, using a large sample questionnaires for empirical analysis and testing for reliability and validity, and laying the foundation for further empirical research (Genus and Iskandarova, 2018) to more effectively support management decisions (Schönherr et al., 2020).

Secondly, the interviewees were essentially at the top of the company. Although each interviewee played an important role in the corporate responsible innovation practices, the company's middle management and employees may have a more in-depth description of this practice and their views may differ from those of top management. In future research, consideration could be given to adding a subset of company personnel other than top management as interviewees to gain a more comprehensive understanding of the corporate responsible innovation practices.

Thirdly, the current study has only studied enterprises in eastern China. However, as the level of economic and technological development varies greatly across different regions of China, the reasons for corporate responsible innovation and their understanding of CRI vary, more regions or other industries with high innovation intensity could be sampled and a larger sample of respondents could be identified in the future to improve the stability and reliability of the study. In addition, single or multiple case studies of typical companies can be conducted to further explore the performance of these companies in responsible innovation practices and to improve the reliability and dynamism of the study.

6 Conclusion

In this paper, based on literature analysis, we conducted 13 interviews with some enterprise representatives in environmental protection enterprises. After coding, summarizing and sorting out, we further clarify the concept and structural framework of corporate responsible innovation, and explored the factors driving environmental protection enterprises to engage in responsible innovation based on a dual perspective from within and outside the corporate. Our study not only expands the literature on responsible innovation, but also enriches the antecedent research on corporate responsible innovation. In addition, our research has practical implications for actual corporate responsible innovation activities and government governance. Finally, we present the research limitations and future research.

Data availability statement

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

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

Author contributions

YL contributed to the derivation of ideas and wrote the Introduction of the paper. LJ contributed to the practical analysis and wrote the literature review and methodology of the thesis. PY wrote the results, discussion, and conclusion. All authors contributed to the article and approved the submitted version.

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Appendix interview outline

- 1) When did you join the company? And what is your position in the company?
- 2) What is the number of R & D personnel in your company? What is the proportion of R & D personnel in the total number of employees?
- 3) What is the annual R & D investment of your company?
- 4) How about the launch of new products developed by your company every year? How did the market respond (social satisfaction)?
- 5) Which stakeholders internal and external the organization will be involved in the innovation process? To what extent will it communicate and negotiate with stakeholders? How to communicate with them?
- 6) As a leader of an innovative enterprise, will you weigh the needs of different stakeholders before making decisions about innovation activities? (For example)
- 7) In the process of innovation, will you let stakeholders monitor the possible negative effects? (For example)
- 8) When there are negative effects in the innovation process, will you let stakeholders jointly evaluate and take measures? (For example)
- 9) What influences your corporate's responsible innovation behavior the most (economic benefits, national policies, laws, industries, competition, personal characteristics, entrepreneurship, etc.)?



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Implications of global carbon governance for corporate carbon emissions reduction

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Global warming not only affects biodiversity, but also threatens human health and wellbeing. As the main source of greenhouse gas emissions, enterprises play a critical role in carbon emissions reduction. However, only a small number of enterprises have disclosed their “low-carbon transition roadmap”, primarily due to the lack of immediate payoffs of green investment, which is disadvantageous to achieve net-zero emissions. First, through case analysis of carbon governance in typical countries around the world, we identify effective emissions reduction measures that firms can learn from. Next, this paper summarizes the multi-dimensional impact framework of corporate carbon emissions reduction. Last, we propose a carbon emissions reduction roadmap for companies from four aspects: companies should 1) actively engage in the carbon emissions trading system, 2) increase the application of green technology, 3) enhance corporate governance structure, and 4) ensure sufficient cash flow for low-carbon transition. This study contributes to the framework of corporate sustainable transition, providing practical references for balancing corporate environmental footprint and value growth.

KEYWORDS

global warming, carbon governance, low-carbon transition, emissions reduction roadmap, sustainable development

1 Introduction

Excessive greenhouse gas emissions are caused by human activities and will lead to global warming throughout both inland and ocean systems (Draper and Weissburg, 2019). Global warming results in land drought (Li et al., 2021), wetland degradation (Zhang et al., 2021), sea-level rise (Hieronymus, 2019), and an increase in the acidity of seawater (Orr et al., 2005; IPCC, 2014). Global warming not only influences the range of species and responses to seasonal events, but also impacts the interactions within and between species (Elert and Fink, 2018), and even leads to changes in biodiversity (Kardol et al., 2011; Chang et al., 2019), species variation (Shao et al., 2019) and death of animals (Muhlfeld et al., 2018).

As the main contributor to global warming and environmental pollution, enterprises play a critical role in carbon emissions reduction (Chen et al., 2022; Jiao et al., 2022; Zhang et al., 2022; Zhao et al., 2022). Therefore, enterprises should take on more responsibilities for reducing carbon emissions (Besio and Pronzini, 2014; Haney, 2017). However, corporate low-carbon activities lack immediate payoffs of green investment. In the short term, a large reduction of cheaper traditional fossil energy may increase the operation cost and enhance financial risks (Tian et al., 2022). The cost increase is a disincentive for enterprises to achieve net-zero emissions. To avoid an operation cost increase, some companies are unwilling to conduct carbon emissions reduction activities while ignoring the carbon performance in the whole

supply chain. For example, the 2050 net zero target set by the Airports Council International Europe (ACI Europe) only covers buildings and land operations, excluding aircraft emissions—which account for 98% of corporate carbon emissions (Rogelj et al., 2021). In addition, some companies use greenwashing to improve the self-image of the funds from investment institutions and shareholders (Liu et al., 2021). However, by relying on false propaganda to create a good environmental image, enterprises will fail to achieve the substantial goal of carbon emissions reduction. Another risk for enterprises is that the exposure to corporate greenwashing led to a lost trust of investors and consumers (Nyilasy et al., 2014; Post et al., 2015). Furthermore, the trust loss causes irreparable damage to the corporate reputation and value.

Then how can enterprises achieve the goal of carbon reduction? From the previous literature, government environmental regulation is an external factor that affects corporate carbon emissions reduction. More and more research has found that the pressure from the government is an important driving force for corporate carbon emissions reduction activities (de Aguiar and Bebbington, 2014; Baboukardos, 2017; Herold and Lee, 2019; Wang et al., 2019; Tian et al., 2022). The external pressure exerted by environmental regulations on enterprises can effectively overcome organizational inertia and form a complementary relationship with the corporate internal governance mechanism (Ambec & Barla, 2002), transforming external pressure into an incentive factor to promote corporate carbon emissions reduction. In addition, the “Porter Hypothesis” believes that appropriate environmental regulation can force enterprises to invest in green technology innovation and form long-term benefits that exceed the cost of environmental legitimacy (Porter and Van der Linde, 1995). With advanced green technologies applied to the production process, enterprises can reduce dependence on the traditional heavy-polluting production methods and effectively avoid extra environmental regulation costs (Berrone et al., 2013).

Previous research focuses on the impact of a single factor on corporate carbon emissions reduction. They overlooked the corporate pro-environmental activities for carbon emissions reduction controlled by a variety of internal and external elements. There are interactions among various factors, which indirectly impact corporate carbon emissions reduction. This paper first summarizes the carbon governance experiences of typical countries (or regions) all over the world and identifies advanced practices of incentivizing enterprises to reduce carbon emissions. Then, based on Institutional Theory, Stakeholder Theory, Natural Resource Based View (NRBV), and theory on Low-carbon Strategy Cost Management, we construct a novel four-dimensional framework for corporate carbon emission reduction. Finally, a corporate carbon emission reduction roadmap is proposed accordingly. Notably, the roadmap for corporate carbon emission reduction is generated from four aspects, including 1) actively participating in the carbon emission trading system; 2) increasing the application of green technology; 3) improving the corporate governance structure; and 4) ensuring sufficient cash flow for low-carbon transformation.

This study has two contributions to the corporate sustainability literature. First, we propose a four-dimensional analysis framework for corporate carbon emission reduction activities. Multiple perspectives explore the critical factors of corporate carbon emissions reduction and provide some suggestions for policymakers aiming to achieve net-zero emissions. Second, we screen out the corporate carbon emissions reduction measures from the carbon governance experience of typical

countries (or regions), and draw a “corporate carbon emissions reduction roadmap”. Our findings will give suggestions for enterprises to promote post-epidemic activities through bottom-up pro-environmental behaviours and green recovery plans (Wan et al., 2021).

2 Typical countries (or regions) carbon governance experience

2.1 Background

Since the United Nations Framework Convention on Climate Change (UNFCCC) was formed in March 1994, many countries start to pay more attention to international cooperation in mitigating climate change. The “Kyoto Protocol” (announced in December 1997) and the “Paris Agreement” (announced in December 2015) have become climate change policies with more participating countries around the world. On 10 November 2021, as the country with the largest total carbon emission and the largest carbon emission *per capita*, China and the US issued the “China-US Joint Glasgow Declaration on Enhancing Climate Action in the 2020s” during the United Nations Climate Change Conference in Glasgow. The declaration promises to further strengthen cooperation and take action in reducing carbon emissions and eliminating global illegal deforestation. These two countries (China and US) will work together to achieve the net-zero goal which was outlined in the Paris Agreement. To achieve the long-term goal of carbon neutrality, countries all over the world must rapidly adjust their policy frameworks to reduce carbon emissions. In this context, emissions trading will be crucial. The Emissions Trading System (ETS) will be an important tool to drive decarbonization. The ETS is a cap-and-trade mechanism based on allocations, as well as a trading mechanism that combines the state and the enterprises. We collected data from countries that are currently mature ETS, countries with developing ETS, as well as countries that are drafting system rules for ETS developments (ICAP., 2022), and disclosure in Figure 1. We found that the EU’s carbon emissions trading mechanism is the most mature, and most of the remaining countries are still in the initial phase.

Since lots of countries join the United Nations Framework Convention on Climate Change (UNFCCC), these countries have faced huge pressure on carbon emissions reduction goals. A reduction in regional carbon emissions or carbon emissions *per capita* is considered an effective carbon reduction. We collected annual total carbon emissions and carbon emissions *per capita* of China, France, Germany, United Kingdom and United States during the period 1995 to 2020 from the Carbon Emission Accounts and Datasets (see Figure 2). We found that the United States and China are the countries with the largest carbon emissions. The total annual carbon emissions in the United States between 1995 and 2020 are about 5,000 million tons. China has experienced rapid industrialization and urbanization in the last few decades. In 2020, total carbon emissions have increased nearly four times compared to 1995, up to 10,000 million tons. Germany, the United Kingdom and France have fewer total emissions, and the overall trend is on a steady decline. The United States is the country with the highest carbon emissions *per capita*. Although total carbon emission has declined in recent years, the carbon emissions *per capita* is still as high as 13.53 tons in 2020. In the last 25 years, the carbon emissions *per*

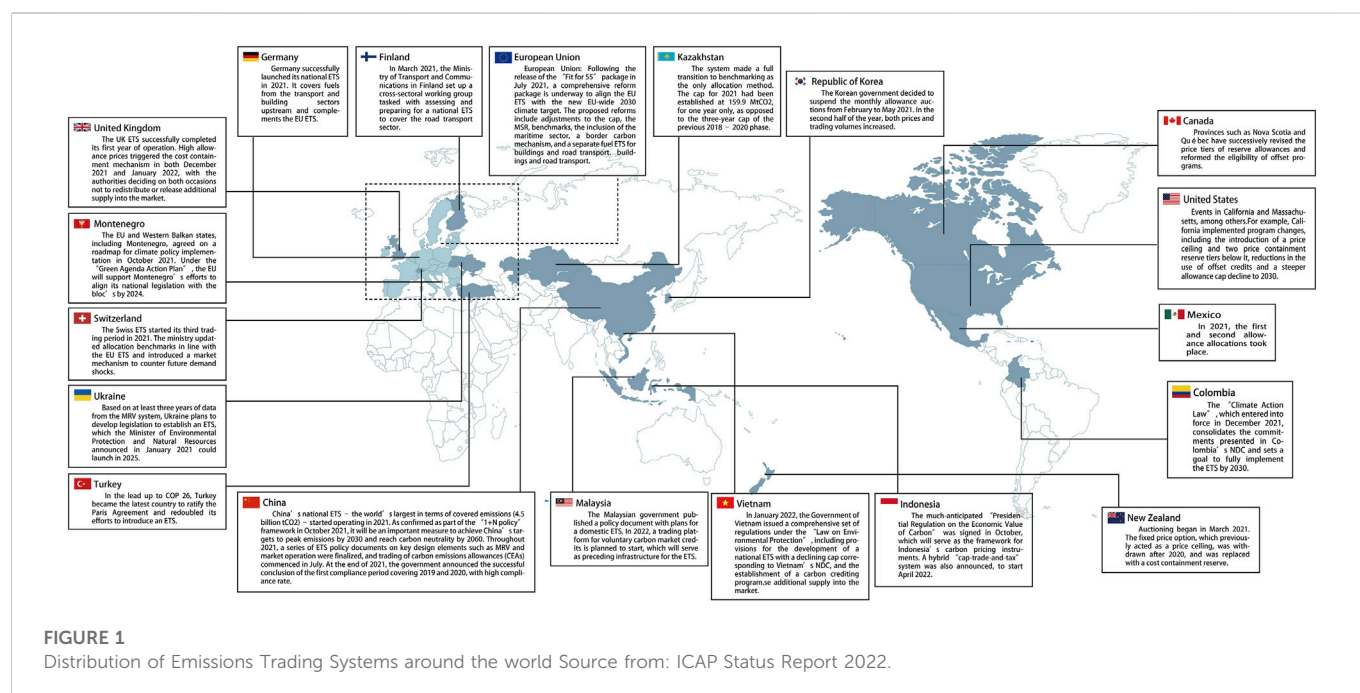


FIGURE 1
Distribution of Emissions Trading Systems around the world Source from: ICAP Status Report 2022.

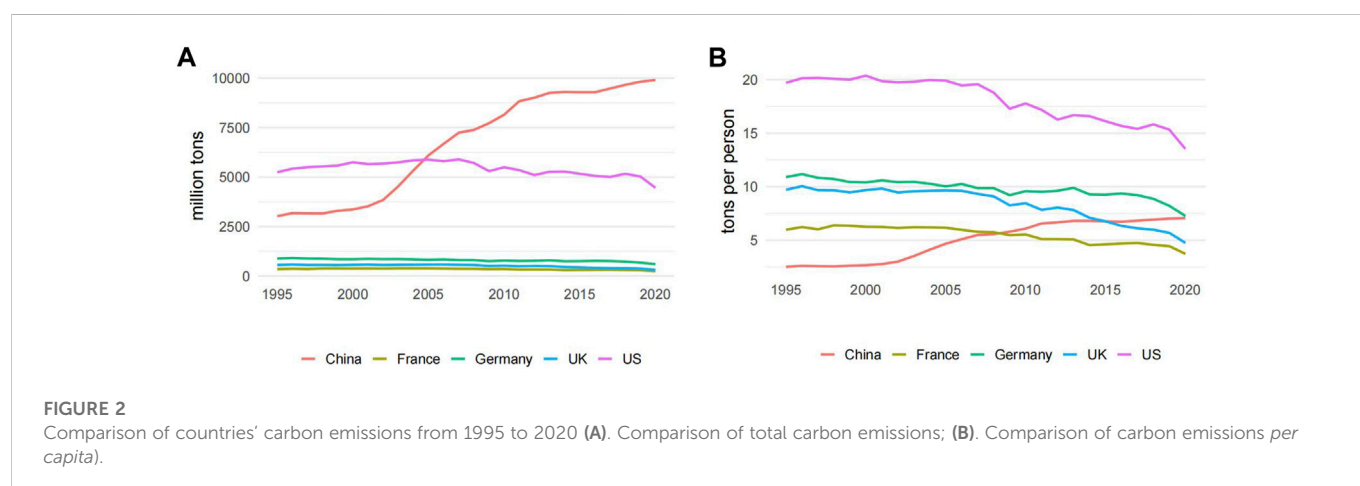


FIGURE 2
Comparison of countries' carbon emissions from 1995 to 2020 (A). Comparison of total carbon emissions; (B). Comparison of carbon emissions *per capita*.

capita of Germany, United Kingdom and France are on a slow decrease, while carbon emissions *per capita* in China have increased. Moreover, China's carbon emissions *per capita* increased rapidly from 2002 to 2011, surpassing France and United Kingdom in 2009 and 2015, respectively. In general, France, Germany and other EU countries, United Kingdom and United States have great achievement of carbon emissions reduction. The rest of this section will summarize corporate carbon emission reduction plans based on the carbon governance experiences of typical countries (or regions).

2.2 European union (EU)

The EU is the main advocate and promoter of the global "Low Carbon Economy" and carbon emissions reduction. The EU has made important contributions to global carbon emissions

reduction by implementing a series of carbon emission policies. The European Commission first launched the European Climate Change Programme (ECCP) in 2000 after the Kyoto Protocol made an 8% of carbon reduction commitment. In 2005, the EU is the first one to establish the European Union Emissions Trading System (EUETS), which successfully introduced the ETS market mechanism into carbon emission governance. The ETS is now well mature and is the first carbon emissions trading system established around the world. The ETS market covers electricity, cement, steel, ceramics, glass, paper, aviation and other industry, laying the foundation for carbon neutrality. The EU has also promulgated strategic policies such as the "2050 Energy Roadmap" and the "European Green Deal" in order to build a competitive low carbon economy and simulate future emission reduction pathways through increased carbon capture storage and the use of renewable energy (Xiao et al., 2022).

EU implements the carbon emissions reduction policy as follows: First, the EU encourages different sectors to work together to achieve a low carbon economy, by promoting renewable energy on a wider scale, including specific industries such as power plants, industrial energy equipment, heating and cooling systems, smart grids and durable energy-saving products, construction, services, public transportation. Second, the EU increases funding for green technology innovation by implementing the NER300 program, which is one of the largest funding projects all over the world. The fund is mainly from the sale of 3 gigatons of carbon emissions right in the third phase of the ETS, as well as private investment and state financing across the EU, mainly to finance the research and development of companies or organizations in renewable energy, carbon dioxide capture and energy storage.

2.3 The United States

The United States has not yet formed a unified carbon market, but has introduced a few carbon emissions reduction initiatives, such as Regional Greenhouse Gas Initiative (RGGI), Western Climate Initiative (WCI) and the mandatory Greenhouse Gas Reporting Program (GHGRP). In 2005, seven states in the northeastern United States and the mid-Atlantic signed the Regional Greenhouse Gas Initiative (RGGI) aiming to reduce greenhouse gas emissions. The US also sets an annual limit for reducing regional carbon dioxide emissions and formulates individual emissions budgets for each state. In 2007, seven states in the western United States and four provinces in Canada signed the Western Climate Initiative (WCI). The WCI sets a common emission cap for energy sources, storage allocations and emission reduction compensation. US Environmental Protection Agency established a mandatory Greenhouse Gas Reporting Program (GHGRP) in 2009. The GHGRP program requires 31 industrial sectors to disclose carbon emission information, which involves 85% of the country's emission sources. Through these carbon emission programs, we can more comprehensively and accurately understand the status of greenhouse gas emissions in the United States. Recently, the US government issued the "Executive Order for tackling the Climate Crisis at home and abroad" and "Clean Future Act", which aim to promote energy transition through green energy innovation, implementing green and clean energy solutions, increasing investment in clean energy, and using green finance to optimize market resource allocation. With the development of clean energy, the United States aims to accelerate low-carbon development in various industries.

The United States has formed a way to promote corporate carbon emissions reduction actively by the use of financial means and ETS market mechanisms. The US government attaches great importance to innovating carbon reduction technologies through government-enterprise cooperation by using government policies. The purposes are to guide ETS market development, increase the enthusiasm of the ETS market, enhance green innovation and maintain the international competitive advantage. To ensure the implementation of the policy, the US government has adopted taxation, subsidies, finance and other measures to affect the corporate cost of production and operation. The US encourages enterprises to voluntarily carry out innovative activities to develop carbon emissions reduction technologies through the ETS market

and to promote carbon emissions reduction in a "bottom-up" voluntary emission reduction model.

2.4 The United Kingdom

The United Kingdom is an advocate and leader of a low-carbon economy, with economic growth of 78% and carbon emissions reductions of 44% between 1990 and 2019. The United Kingdom low carbon policy mainly includes 1) low carbon legislation, 2) low carbon strategy, and 3) fiscal and tax subsidies. Firstly, low carbon legislation. In 2008, the Climate Change Act (CCA) was formed, every 5 years as a stage, and the United Kingdom has different carbon budget levels at different stages. The bill clearly puts forward long-term low carbon development goals, and legally stipulates enterprises' carbon emission constraints. Next is the low carbon strategy. British issued the energy white paper "Our energy future - creating a low-carbon economy" in 2003. This is the first time the concept of a "low carbon economy" was proposed and it aims to solve the emission problems by reducing the use of oil, natural gas and coal energy. United Kingdom issued "The United Kingdom Low Carbon Transition Plan" in July 2009, which claims the low carbon industry as a new growth point of the United Kingdom economy. Last, fiscal and tax subsidies. In 2001, the United Kingdom established the "Carbon Fund". The "Carbon Fund" from climate change taxes and landfill taxes aims to help enterprises to develop low-carbon technologies. United Kingdom Carbon Trust established in 2001, which is to "accelerate the transition to a low carbon economy by working with businesses and the public sector to reduce carbon emissions and develop commercialized low carbon technologies". The Green Investment Bank (GIB) was established in the United Kingdom in 2012, as the world's first publicly funded bank to finance low-carbon projects, with the aim of mobilizing private capital into the green energy sector.

In addition to promulgating a series of policies and regulations, in 2020, the United Kingdom has also formulated a comprehensive support policy for enterprises in terms of capital, technology and talent. The "Ten Point Plan" has mobilized 12 billion pounds of government investment for green innovation. At the same time, the "Ten Point Plan" encourages private sector investment and unleashes the creativity of capital to generate and develop new green technology. The United Kingdom helps investors to obtain funding for green projects by building London as a global green financial centre. In terms of technical support, enterprises have greatly reduced the cost of low-carbon technologies by acquiring the latest advanced equipment supported by the government. In terms of talent support, the United Kingdom also trains workers in green job skills through the "Lifetime Skills Guarantee" project to meet the job requirements of emerging green industries.

3 The framework of enterprises carbon emissions reduction

The four-dimensional framework for corporate carbon emissions reduction includes Institutional Theory, Stakeholder Theory, Natural Resource Based View (NRBV), and Low-carbon Strategy Cost Management (Geels, 2014; Haley, 2014; Penna and Geels, 2015). Enterprises face pressure from various entities in the economic

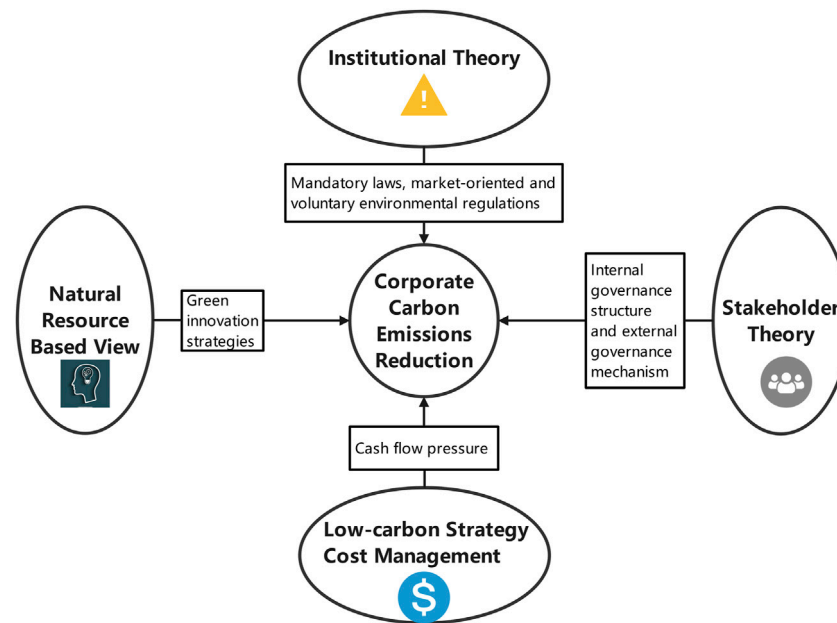


FIGURE 3
Corporate carbon emissions reduction framework.

network (such as board directors, shareholders, and suppliers) and social and political networks (such as the government, environmental regulatory authorities, and other NGOs). Enterprises are responding to these pressures by implementing a variety of emission reduction strategies (Figure 3), including.

- Mandatory laws, market-oriented and voluntary environmental regulations, for example, emissions trading systems, emissions taxes, subsidies for emission reduction, and policies for pollution emission limitation (Magat, 1978; Milliman and Prince, 1989; Milliman and Prince, 1992);
- Internal governance structure and external governance mechanism, board directors, CEO, institutional investors, the law and the media (Kock et al., 2012; Haque 2017; Zhang et al., 2021; Liu et al., 2022; Ludwig and Sassen, 2022);
- Green innovation strategies such as R&D investments or green technological development (Tidd et al., 2005; Sohag et al., 2015);
- Cash flow pressure such as higher environmental costs and increased investment in environmental protection technologies (Su et al., 2020; Alam et al., 2022; Tao et al., 2022).

First, Institutional Theory explains the role of policies and regulations in corporate carbon emission reduction (Greenwood and Hinings, 2017). Pigou. (1920) was the first to put forward the problem of pollution externality, and proposed Pigouvaintax to solve the internalization of pollution cost. Coase (1960) proposed to solve the problem of externality by marketing and property right. Then, based on the Coase theory, Dales (1968) introduced the concept of property rights into the field of environmental pollution control, he first proposed the concept of the Emissions Trading System (ETS). Subsequent research found that mandatory laws, market-oriented and voluntary environmental regulations promulgated by the government or regions will effectively reduce corporate carbon emissions. For

example, emissions trading systems, emissions taxes, subsidies for emission reduction, and policies for pollution emission limitation (Magat, 1978; Milliman and Prince, 1989; Milliman and Prince, 1992). In addition, the implementation of market-based climate policies represented by the emission trading system (ETS) can motivate companies listed in the Chinese A-share industrial sector to gain financial profits by reducing carbon emissions (Yu et al., 2022).

Second, the external pressure exerted by environmental regulations on enterprises can effectively overcome organizational inertia and form a complementary relationship with the internal governance mechanism of enterprises (Ambec and Barla, 2002), transforming external pressure into an incentive factor to promote corporate carbon emission reduction. Previous research found that firm size, oversight by corporate social responsibility committees, and regular disclosure of sustainability reports can help reduce carbon emissions from South African firms (Córdova et al., 2018). However, political relations, enterprise scale, industry category and regional differences affect the carbon emission reduction initiative of Chinese enterprises (Jiang et al., 2021). At the same time, due to the difficulty of coordinating the interests of all parties in the issue of carbon externalities, corporate governance is regarded as another way to deal with climate risks (Azar et al., 2021; Goud, 2022). According to the Stakeholder Theory, stakeholders of an organization are those who can influence or be influenced by the overall objectives (Freeman, 1984). Board directors play a critical role in managing resources in corporate operations (Hillman and Dalziel, 2003), and a positive role in corporate governance and avoiding environmental risks (de Villiers et al., 2011; Shaukat et al., 2016). Previous research found that board independence (Liao et al., 2015; Post et al., 2015), board gender diversity (Glass et al., 2016; Atif et al., 2021), and Chief Executive Officer (CEO)'s experience and personality (Walls and Berrone, 2017; Arena et al., 2018) may affect the corporate carbon emissions reduction activities. Recent studies have also found that the board's

environmental orientation is helpful to increase environmental-related investment and effectively reduce carbon emissions (Dixon-Fowler et al., 2017; Moussa et al., 2020; Tian et al., 2021). In addition, shareholders and other stakeholders need to pay more attention to the disclosure of corporate carbon information (Matsumura et al., 2014). At present, most countries do not force all companies to disclose carbon emission information, resulting in weak constraints on corporate carbon emissions by shareholders, institutional investors or the media.

Third, the “Porter Hypothesis” believes that appropriate environmental regulation can help force enterprises to innovate in green technology and form long-term benefits that exceed the cost of environmental regulation (Porter and Van der Linde, 1995). Enterprises that apply advanced green technology to the production process can reduce dependence on traditional heavy-polluting production methods and effectively avoid environmental supervision costs (Berrone et al., 2013). The forced effect of environmental regulations on corporate green innovation are from external pressure of stakeholders and the incentive factors within enterprises (Cole et al., 2013; Lee and Min, 2015; Ahmed et al., 2016; Shi et al., 2022). Xu et al. (2016) found that investors assign lower valuations to companies that were punished for environmental protection, and higher valuations to companies that committed on green development. Therefore, in terms of internal incentives, green innovation can enhance the perceptions of stakeholders in enterprises green transition and reduce the negative expectations of stakeholders on the pollution of the environment by enterprises (Buysse & Verbeke, 2003). According to the Natural Resource Based View (NRBV), enterprises increase investment in long-term research and development (R&D) for environmentally friendly products, processes and technologies, rather than focusing on short-term profit, R&D expenditure will be beneficial to enhance corporate environmental performance and sustainable competitiveness (Hart, 1995). Tian et al. (2020) document that green innovation significantly enhances corporates’ green technology and environmental performance. In addition, corporate green innovation is helpful to reduce energy consumption and waste in production (Alam et al., 2019), and will enhance energy and production efficiency, ultimately reducing the carbon emission intensity of the supply chain.

Fourth, in response to stricter environmental regulations, companies have to internalize various costs of carbon emission reduction, such as disclosure costs, compliance and management costs, and additional capital expenditures for technology upgrades to reduce emissions. The United Kingdom petrochemical industry reduced emissions by 88% between 1990 and 2019, mainly due to the closure of petrochemical plants, switching fuels to natural gas and electricity, and green technology upgrades to improve energy efficiency (Geels, 2022). Even with immediate results, the changes induced by the low-carbon transition increase a company’s operating leverage, which further translates into higher uncertainty in firms’ future cashflows (Oestreich and Tsiakas, 2015). Low-carbon Strategy Cost Management specifically includes the *ex-ante* cost accounting for the prevention of environmental pollution, the interim cost accounting for environmental maintenance and the *ex-post* cost accounting for environmental pollution control. Expanding the scope and period of environmental cost accounting will help the entire industry chain to manage environmental costs and maintain corporate cashflows. Corporate cash flow affects carbon emissions reduction in two ways. First sufficient cash flow of a company is the

foundation for energy transition from traditional fossil energy to renewable energy. Energy transition and renewable energy consumption will reduce carbon emissions. Especially after the 2019 coronavirus pandemic, clean energy supply chains were disrupted, which bring greater challenges to corporates’ low-carbon transformation (Tian et al., 2022). With the shortage of low-carbon energy supply and rising costs, enterprises need more abundant cash flow to ensure low-carbon transition (Su et al., 2020; Alam et al., 2022). Second, corporate green innovation generally requires long-term R & D investment and sufficient cash flow of enterprises to promote green innovation and new technology applications. Cash flow and green innovation are important for energy consumption reduction, energy efficiency, and ultimately reduce corporate carbon emissions.

4 Corporate carbon reduction roadmap

From the experience of Carbon Governance in typical countries (or regions) around the world, we find that the laws and regulations that keep pace with the times, the unified carbon accounting and carbon management methods, the mature management institutions, and carbon financial products are the main methods for carbon emissions reduction. At the same time, enterprises are facing the pressure of carbon emission reduction in economic and social fields. Then, how can enterprises carry out substantial carbon reduction activities? We have drawn a corporate carbon emissions reduction roadmap based on the four-dimensional framework for corporate carbon emissions reduction (Figure 4).

4.1 Actively engaging the carbon emissions trading system

In the carbon emissions trading system, the government can allocate initial emission reduction responsibilities to companies with high energy consumption, high pollution and high emission. Enterprises with excess emissions need to purchase carbon emission rights through the carbon trading system. Companies reduce carbon dioxide emissions through various measures and sell their excess carbon emission allowances through carbon exchanges.

Corporations take the initiative to participate in this market transaction activities with carbon emission rights, which can bring two benefits for enterprises. First, companies used to reduce carbon emissions just to fulfil their social responsibilities. After carbon emissions trading is implemented, surplus emission allowances can be traded. The more the balance, the greater the benefit of the companies, which can directly reduce the energy cost. Second, for some companies with excess emissions, the economic losses caused by excess emissions are not obvious, however, with the carbon emissions trading system, excess emissions will bring higher production costs to enterprises. The corporate production costs linked with carbon emission will directly reduce high-polluting and energy-intensive products while increasing investment will strengthen carbon emissions reduction.

4.2 Corporate governance structure

The Board director plays a critical role in corporate carbon emissions reduction activities by supervising corporate activities and managing and providing resources to help implement carbon

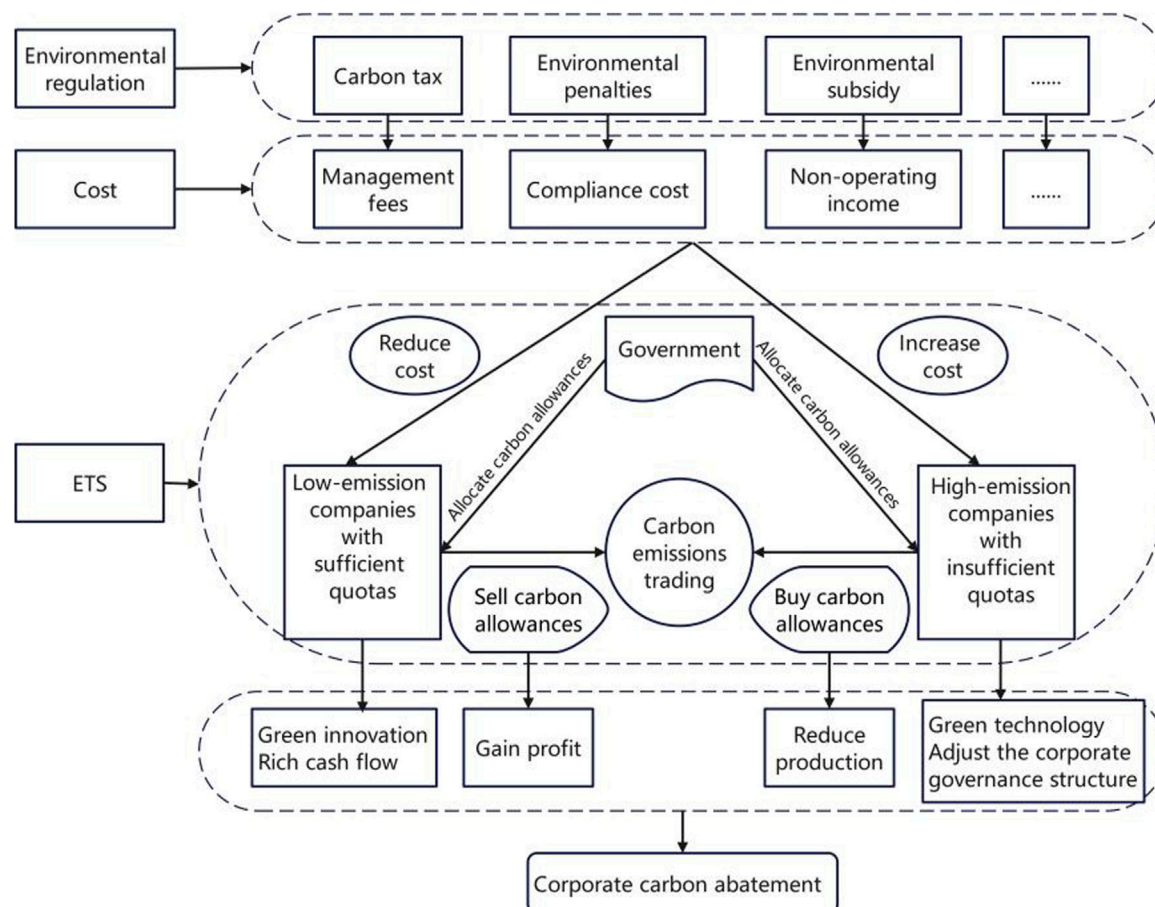


FIGURE 4
Corporate carbon emissions reduction roadmap.

emission policy. Some companies still lack attention to carbon neutrality goals. Some other companies have awareness of carbon neutrality goals but without any guidance on how to act, as there are no clear low-carbon transition measures. Therefore, enterprises need to exert the ability of the board directors to integrate resources and strengthen carbon emissions reduction activities. Furthermore, enterprises should strengthen the monitoring, statistics, accounting and analysis capabilities of energy consumption and carbon emissions, and actively carry out carbon quantification.

In addition, enterprises should continuously strengthen the level of employees' low-carbon management and carbon asset trading through employee training. Enterprises should make more communication with the government, the public and financial investment institutions through environmental protection information disclosure, and continuously enhance the company's environmental protection image, thereby increasing the corporate value.

4.3 Application of green technology

Green technology means that the enhancement of green innovation is critical to achieving carbon emissions reduction and

improving energy efficiency through technological upgrading, reducing dependence on fossil energy, and increasing the utilization rate of renewable energy. Enterprises should encourage the application of green technology and control the carbon emissions of the whole industry chain. The traditional fuels used by enterprises include coal, coke, blue carbon, fuel oil, gasoline and diesel, liquefied gas, natural gas, coke oven gas, and coal bed methane. The important step in carbon emissions reduction is the production process, however, there are still many processes of fuel purchase and storage, processing and conversion, and use that need to improve. For example, to reduce the loss of organic components in fuel consumption, boilers should meet the design requirements and other combustion equipment to reduce energy waste.

The increase in green technology, such as China's carbon emissions trading system, can enhance corporate carbon emissions reduction and obtain profits. The emission trading market will encourage energy-saving and low-carbon energy projects listed in Chinese Certified Emission Reduction (CCER) and participate in carbon trading. The cost of CCER projects will bring some funding for enterprises by selling carbon emission right, therefore, emission trading not only promotes the development of energy-saving and low-carbon energy, but also increase the companies' cash flow and capital structure.

4.4 Guaranteed cash flow

Under the conditions of a market economy, corporate cash flow determines the survival and development ability of the enterprises. Sufficient cash flow ensures that enterprises have more confidence in renewable energy consumption under the impact of uncertain events. For example, the supply chain of renewable energy has been cut off due to the COVID-19 pandemic, resulting in the price of renewable energy being risen. Enterprises that consume renewable energy will reduce the use of fossil fuels in the production process, phase out outdated production capacity, and reduce carbon emissions. In the long run, this will reduce corporate compliance costs and the use of carbon allowances. The extra carbon allowances can trade in the emission trading system, which will bring financial benefit and value growth. As corporate profits increase, more funds will be used for R&D investment, which will improve green technologies and reduce carbon emissions. The circular process will form a green and healthy corporate carbon emissions reduction plan.

Enterprises should incorporate environmental protection costs into enterprise cost management, and speed up the cash flow of the enterprise by establishing an appropriate inventory mechanism and credit policy. The main purpose is how to speed up the turnover of enterprise inventory and the recovery of accounts receivable, as well as how to reduce inventory occupation cash and bad debt losses, so that enterprises can maintain a reasonable level of cashflows.

5 Conclusion and discussion

Carbon neutrality is a systematic and comprehensive transformation carried out by countries at the economic and social levels. Enterprises should systematically invest upgrade technology research and development, operation management, investment and financing, to change the energy structure and carry out green transformation.

This paper summarizes the multi-dimensional effect of factors on Corporate carbon emissions reduction through literature reviews and emission data. The influencing factors mainly focus on environmental regulation, green innovation, corporate governance and cash flow. A basic carbon emissions reduction roadmap is proposed for enterprises, including four aspects: carbon emissions trading system, green technology and innovation, improving the corporate governance structure and ensuring sufficient cash flow.

With the experience of carbon governance around the world, carbon emissions reduction requires multi-party collaboration and continuous operation. Enterprises should strengthen their awareness of carbon asset management and take the initiative to engage in the emission trading system. The government and financial institutions should also suppurate the corporates' low-carbon behaviour, and more efficient cooperation will ultimately help to achieve the goal of net-zero emissions.

To achieve the goal of net-zero emissions, enterprises should actively engage in carbon emissions trading systems, the global carbon trading system also needs to optimize firm performance. Carbon emissions trading systems in various countries are generally faced with three challenges: One is the lack of policy design. The regulation system of the total amount and production capacity are not consistent. The reform of energy supply systems and other emission trading systems is not the most efficient, which makes

carbon emissions reduction more challenging. Second, the government lacks the capability to supervise. From the experience of the existing carbon emissions trading system, the government's capability is critical and plays an important role in carbon emissions reduction. The cooperation between governments and emission-reduction companies needs to enhance effective measures to ensure the operation of the policy. Most national carbon emissions trading systems still use "top-down" allocation systems and trading rules, which will make the long-term investment participants encounter bottlenecks. Therefore, it is necessary to design an appropriate carbon emissions trading system to stimulate enterprises' vitality to participate in carbon emissions trading systems. Lastly, it is necessary to stimulate the corporate internal motivation to actively participate in carbon emissions trading, which will create an incentive for companies to invest in net-zero emissions.

Governments around the world should also take the initiative to establish an effective carbon pricing mechanism. On the one hand, governments should rationally allocate quotas and set prices for "emission-controlled enterprises" in carbon emissions trading systems. Emission-controlled enterprises include petrochemical, chemical, building materials, steel, non-ferrous, paper, electric power, aviation and other industries. Setting carbon emission quotas for enterprises will strengthen enterprise carbon asset management and encourage enterprises to actively reduce emissions. On the other hand, carbon prices should play a guiding role in corporate and consumer activities. Compared with the carbon emissions reduction of production activities, consumer behaviour is more difficult to control and calculate. Companies should take the initiative to engage the carbon emission system and realize the importance of carbon emissions reduction. This is a gradual transition from production to consumption, which will eventually persuade consumers to adopt low-carbon behaviour. Therefore, it is crucial to encourage companies to take the initiative to engage in the carbon emissions trading system, and then subsequently, influence consumers' low-carbon behaviour. It is particularly important to formulate reasonable carbon pricing.

Banks and other financial institutions need to upgrade the carbon financial product system as soon as possible and develop diversified carbon financial derivatives. The carbon financial markets around the world are emerging and developing, and the carbon financial products include carbon futures, carbon options, carbon forwards, and carbon swaps. However, the long-term extensive economic structure restricts the development of carbon finance, resulting in low financing efficiency in the carbon financial market. Most enterprises need to change their business model and eliminate outdated production. In the case of companies' shortage of funds, bank loans are the main way to ensure the cash flow of normal operation of enterprises. The carbon financial trading market generally has problems of insufficient liquidity and low trading activity. Due to the small scale of the carbon financial market and the single product variety, enterprises tend to be conservative in emission reduction and lack carbon financial trading willingness.

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: methodology, validation, supervision, writing original draft preparation. GY: software, formal analysis. YZ: writing review and editing. QW: writing review and editing. All authors have read and agreed to the published version of the manuscript.

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Nexus between environmental sustainability, good governance, financial inclusion, and tourism development in Bangladesh: Evidence from symmetric and asymmetric investigation

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Over the past decade, tourism's contribution to economic Section progress has emerged as an alternative avenue for socio-economic development, especially in the productive economy with natural beauty. On the other hand, the potential effects of tourism on the environment have also been unveiled in the literature, along with macroeconomic misbehavior due to erratic environmental changes. However, the study's impetus is to inspect the reaction of tourism contribution to Bangladesh's economy from 1991–2019 with ecological sustainability, good governance, and financial inclusion in the empirical assessment. With the implementation of both linear and non-linear frameworks, the present study has explored the elasticities of core explanatory variables on explained variables; for directional causality, the novel Fourier Toda and Yamamoto causality test has been executed. According to the combined cointegration test, Bangladesh has a long-run association between environmental sustainability, good governance, financial inclusion, and tourism development. Inferring from long-run symmetric and asymmetric cointegration, the test statistics revealed statistically significant at a 1% level, suggesting the long-run relations in the established empirical model. Considering the linear autoregressive disoriented lagged, the study established a negative and statistically significant linkage between environmental sustainability and tourism contribution, suggesting that the excessive inflows of carbon emission that environmental degradation dwindles the progress of tourism contribution. Whereas a positive and statistically significant influence runs from good governance and financial inclusion to tourism development, the suggestion of easy access to financial services and effective institutional activities prompts tourism activities, especially in the long-run. The asymmetric investigation established non-linearity in the empirical model for the long and short-run. In terms of asymmetric coefficients, the study unveiled the positive and negative shocks of environmental sustainability exposed negatively and statistically significant. In contrast, the asymmetric shocks of financial inclusion and good governance established positive and statistically substantial Bangladesh tourism development in the long and short-run. The directional causality assessment revealed bidirectional causality running between explanatory variables to tourism development.

KEYWORDS

environmental sustainability, good governance, financial inclusion, tourism development, autoregressive disoriented lagged, nonlinear autoregressive disoriented lagged, Bangladesh I

1 Background of the study

The economic advantages of tourism to a nation or a province, state, department, municipality, or another local region within a country consist of sales and output, labor wages, and employment. Tourism is “the actions of individuals going to and staying in locations outside their customary environment for less than 1 year for pleasure, business, or other objectives” (Carrascal Incera and Fernández, 2015). Tourists provide vital funds to local businesses, governments, and citizens; moreover, companies that service visitors and those that supply them are crucial to the local economy, and its executives, authorities, employees, and dependents must recognize this to make informed private and public policy choices (Wang et al., 2022). Tourism boosts local economies by creating jobs and generating revenue *via* increased output and visitor spending. The tourist multiplier is the total increase in output, labor pay, and employment in a region due to interindustry links. The economic impact of tourism is measured by a “multiplier,” which directly affects the number of money tourists spend in a certain area (Li and Qamruzzaman, 2022a; Xiao and Qamruzzaman, 2022).

The importance of the tourism industry to the economy has grown in recent decades, and so has the number of foreign tourists. The World Travel and Tourism Council estimates that As a result of continued limits to mobility, the travel and tourism sector's contribution to the global GDP will drop from 10.3% in 2019% to 5.3% in 2020, even though it contributed 10.3% in 2019. In 2021, the share reached 6.1% after having previously been at 5.9%. In addition, the revenue from tourism has provided an additional channel for exports, which has aided the balance of payments in many countries. Profits from tourism have grown into a significant industry, contributing to a rise in the number of people employed, the purchasing power of families, and tax revenue collected by governments throughout the world. Regarding tourism's nexus to several economic, the study documented two vines of evidence in the literature. First, the positive association that tourism development accelerated economic growth (Alam, 2022a; Toubes and Araújo-Vila, 2022; Wu et al., 2022a; Wu et al., 2022b), financial development (Kumar, 2014), foreign direct investment (Arain et al., 2020), capital formation, poverty reduction and human capital development (Thrane, 2008). The second line of empirical studies has explained the destructive nature of tourism development in the economy through environmental degradation by increasing carbon emissions (Liu et al., 2011). However, in terms of tourism growth deterrents, the existing literature has exposed several economic factors that positively influence tourism's contribution to the economy, such as foreign direct investment (Ivanovic et al., 2011). There is ample evidence that tourism benefits host communities directly and indirectly by generating new products and services, increasing local economies, and generating new revenue streams (Archer and Fletcher, 1996). However, some of these benefits could have unintended negative effects on other people and production variables (Hassan et al., 2022). The economy's structure (the volume of imports required in the manufacturing process) and the commodities purchased by visitors influence the leakage. Understanding how tourist spending impacts labor and capital revenues distribution to the various socio-economic actors is crucial to properly account for distributional effects (Wattanakuljarus and Coxhead, 2008).

The present study has considered environmental sustainability, financial inclusion, and good governance in tourism development.

According to existing literature, the nexus between tourism-led environment has produced one directional investigation in most cases which is the impact of tourism development on the environment and documented adverse association, suggesting that the detrimental role of tourism in the process of environmental degradation (Raza et al., 2017; Shahbaz et al., 2021; Teng et al., 2021); Villanthenkodath et al., (2022b), however, the positive effects of tourism on carbon reduction has established in the literature as well (Tong et al., 2022). The role of institutions and economic freedom in explaining observed economic growth and performance disparities is an important study area. The economic literature has shifted from focusing on inputs and technology to a wider understanding of growth conditions (Gwartney et al., 1999). Good governance is required to provide (Dixit, 2009) the protection of property rights, the enforcement of contracts, and collective action. According to Khan et al., (2021), the beneficial effects of good governance stem mostly from two sources. First, it decreases transaction costs, making markets more efficient. Second, excellent governance allows markets to “overcome persistent market shortcomings in distributing assets, obtaining productivity-enhancing technology, and preserving political stability in circumstances of rapid societal transition”.

Financial inclusion allows businesses and entrepreneurs in the tourist industry to access official financing sources and bolster the money they need for their endeavors. According to Ayyagari et al., (2011), having access to financial resources is directly connected to the phenomenon of innovation, which, in turn, drives economic development *via* an increase in productivity. In developing nations with prevalent bank-based financial systems, bank-based financial inclusion significantly simplifies the process of financial inclusion. It contributes to a more rapid acceleration of economic development *via* inclusive growth (Dai et al., 2022). Furthermore, mobile payment systems have made significant strides toward global adoption in the recent decade. As the mobile phone has become an indispensable component of an individual's day-to-day existence, it has grown more ingrained in their travel experiences in recent years. Through financial inclusion, travelers are given much-needed access to mobile payment systems, allowing them to hassle-free pay for the travel-related goods and services they purchase (Yang et al., 2021). Additionally, small and medium-sized businesses (SMEs) in the tourist industry with access to money and giving people access to mobile payments and transfers are two crucial components of a sustainable tourism development strategy, especially in developing nations. Low and middle-income small and medium-sized enterprises (SMEs) in the tourist industry rely heavily on backward and forward connections to the global value chains in the industry, and this is only possible with access to financing (Alam et al., 2022c).

The potential contribution of the study is as follows; first, it refers to the nexus between environmental degradation and tourism; existing literature predominately focuses on tourism's impact on the environment; however, the potential role of environmental sustainability, which is the reduction of carbon emission on tourism development, has yet to investigate extensively. On this note, the present study has implemented the empirical relationship between environmental sustainability and tourism development to document the possible effects on tourism contribution. Second, according to the literature, easy access to financial services, efficient financial intermediation, and good governance have positively influenced tourism. On the other hand, the possible effects of

environmental degradation on tourism have yet to be extensively investigated and completely ignored in terms of tourism development in Bangladesh. The study intended to mitigate the literature gap by exploring fresh insight. Third, it is apparent in the existing literature that financial development and good governance influenced environmental quality; thus, the present study considered the interactive term between ecological sustainability and financial inclusion ($ES*FI$) and environmental sustainability and good governance ($ES*GG$) for documenting the mediating effect on tourism development.

Conferring to the study findings, it is obvious that tourism development in Bangladesh relies on environmental quality improvement, suggesting that carbon emissions cause ecological degradation, which leads to a negative impression of tourism progress. On the other hand, the connection between financial inclusion, good governance, and tourism development has been exposed positively and statistically significant, indicating that financial inclusion is easy to access financial services from financial institutions, and efficient financial intermediation entices international tourism arrivals; as a result, the process of tourism development has intensified. For good governance, it is confirmed an ambiance for political stability and institutional effectiveness, accelerating tourism development trends by protecting tourists' interests. The asymmetric investigation established non-linearity in the empirical model for the long and short-run. In terms of asymmetric coefficients, the study unveiled the positive and negative shocks of environmental sustainability exposed negatively and statistically significant. In contrast, the asymmetric shocks of financial inclusion and good governance established positive and statistically substantial Bangladesh tourism development in the long and short-run. The directional causality assessment revealed bidirectional causality between explanatory variables and tourism development.

The remaining structure of the paper is as follows: The literature survey and hypothesis development are available in Section II. The variables definition and methodology of the study are explained in Section III. Section IV deals with the mode of estimation and interpretation. Discussion of the study is reported in Section V. finally, the conclusion and policy implications are exhibited in Section VI.

2 Literature survey

The tourism literature has mostly focused on questions about the link between economic expansion and the expansion of the tourism industry. Increasing tourists means more money and jobs, which may boost a country's economy. The tourist-led growth (TLG) concept, popularized by (Balaguer and Cantavella-Jordá, 2002), is only one-way tourism influences economic development. Regarding tourism development, two studies have been initiated, that is, the impact of tourism on several economic factors and the determinants of tourism development.

2.1 Environmental sustainability and tourism

The nexus between tourism and environmental sustainability, inferring the existing literature, is the domain of study findings

available. First, a growing number of studies have revealed a detrimental role of tourism development in the economy is environmental degradation (Raza et al., 2017; Sharif et al., 2020; Teng et al., 2021; Andriamahery and Qamruzzaman, 2022; Villanthenkodath et al., 2022a; Li and Qamruzzaman, 2022b; Ma and Qamruzzaman, 2022; Xia and Qamruzzaman, 2022). For example, in the case of India (2022a) exploded the role of tourism development in the process of losing the environmental quality with the application of ARDL bound testing approach for the period 1995Q1–2018Q4. The study documented a positive and statistically significant association between tourism development and the level of carbon emission into the ecosystem, suggesting the contributory role of tourism development in environmental degradation. Further evidence in the study of Villanthenkodath et al., (2022a) shows that an increase in tourism negatively influences ecological quality. Still, a shift in the economy's basic structure has a positive impact, and a break in the series implies that tourism has very little effect on carbon emissions. Moreover, the study has established that economic expansion improves environmental quality. However, the usage of energy is found to decrease the ecological rate. Many international organizations and institutions have produced reports highlighting the potential positive effects sustainability may have on tourist development and the processes related to the economic growth of destinations. These organizations have tried to justify why vacation spots should put money into becoming more environmentally friendly. UNEP found in 2011 that the tourism industry was more interested in investing in environmental sustainability. In another UNWTO report, sustainable tourism is called an "instrument to support economic and social improvement" (2013: 12). For its part, the Global Sustainable Tourism Council is working to show that eco-friendly tourism is profitable by minimizing damage to natural areas, boosting the local economy, and protecting irreplaceable cultural relics (Gharib et al., 2022).

The term "environmental quality" describes how well-maintained the area's natural characteristics are and how easily they can be damaged by human activity (Mihalič, 2000). The connection between tourism and the natural world is frequently disregarded as irrelevant and seldom subjected to in-depth study. Despite this, it is obvious that people's perspectives on the environment have undergone significant shifts with time, particularly concerning tourism and numerous other facets of human growth (Butler, 2000). Regarding a nation's overall economic health, the tourism industry is crucial. However, the tourist sector and the environment are increasingly interrelated. The success of the tourist business depends on the natural and built environments being in good condition. Even though tourism may benefit the environment, the two are frequently considered independent (Rabbany et al., 2013). The influence on the environment, which has both favorable and unfavorable elements, is constantly evolving due to the ongoing growth of tourism. There are many different ways in which tourism can contribute to the preservation of the natural environment. Tourism can safeguard endangered areas and the natural environment. Visitors' entrance fees can maintain and manage ecologically complex regions. Further, governments may collect the funds they need for environment management *via* charges, tax payments, taxes on the sale or rental of leisure equipment, and royalty payments for events like hunting and fishing. This revenue can be utilized toward various comprehensive preservation initiatives and activities, such as

paying park ranger salaries and the upkeep of park facilities (Camarda and Grassini, 2003). Tourism has the potential to significantly contribute to the protection of the environment, the preservation and restoration of biological diversity, and the responsible use of natural resources. It is possible that national parks and wildlife preserves would be established to protect natural areas and pristine landscapes because of their aesthetic value (Hamid et al., 2022).

Even though tourism has a beneficial effect on economic expansion, it also significantly affects CO₂ emissions. The more appealing a destination is (typically as a result of its great biological or cultural values), the more likely it is to become popular, and the greater the likelihood that it will become degraded as a result of heavy visitation, which may result in a decrease in the overall quality of the experience (Hillery et al., 2001). Environmental costs are associated with tourism, including transportation, attractions, and hotels. These costs include pollution from tourist traffic, rude conduct from visitors, and excessive energy use. (Zhao and Min Li, 2018). According to (Rabbany et al., 2013), some direct environmental impacts are affected by a country's tourism sector. To name a few: deteriorating water and air quality, excessive noise pollution, excessive solid waste and littering, altered and fragmented ecosystems, effects on animals, impacts on aesthetics and culture, loss of biological variety, ozone depletion, and climate modification. In modern economies, private amenity construction inside public protected areas threaten conservation as a result of tourism. In underdeveloped nations, tourism is utilized to fund conservation initiatives in public and privately maintained or communal areas (Buckley, 2011).

The previously described negative consequences of tourism on the environment not only harm or disturb the natural and cultural resources upon which tourism development relies but also influence tourists' experiences. This brings up the challenge of improving tourists' experience while reducing the damage they cause to the surrounding environment (Zhong et al., 2011). The tourist sector has already started preparing to lessen the impact of its activities. This includes industry- and government-led initiatives, financial contributions, enhanced environmental planning and management, public education and outreach campaigns, and stricter preservation, protection, and disclosure mandates (Rabbany et al., 2013). In addition (Paramati et al., 2017), found that the environmental damage in Western Europe is lessened because of tourism. The introduction of environmentally friendly technology and ecologically responsible tourist activities were highlighted as potential sources of tourism's ameliorative influence on environmental deterioration. According to (Zhong et al., 2011), the natural and social/cultural settings significantly determine how successful a destination's tourist industry will be. Therefore, it is of the utmost importance to maintain or even increase the quality of the tourist environment at a given site. Pollution can degrade the attraction of natural elements such as spectacular landscapes, biological hydrologic structures, clean water, healthy air, and wildlife (Mihalič, 2000).

This should not be used as an excuse to disregard the importance of environmental quality in a more general sense. Generally, tourists will not return to polluted, unclean, or unpleasant sites if comparable alternatives are available at similar prices (Butler, 2000). Environmental quality is an important part of perceived quality, which is a crucial variable for customers because it can

significantly influence the likelihood of re-visiting and boost the profitability and attractiveness of tourism destinations. According to (Sadat and Chang, 2016), there is a significant connection between the environment's quality and the satisfaction level experienced by tourists. Therefore, increased tourist satisfaction and favorable impressions of the surrounding environment would benefit the likelihood of a return visit.

H1 Environmental Sustainability augments tourism development

2.2 Financial inclusion and tourism development (literature review)

Access to institutional funding, such as bank loans, may help tourism-related firms and entrepreneurs grow and thrive. Access to capital, according to Ayyagari et al. (2011), is a direct result of a country's rate of innovation, which in turn drives access to capital *via* an increase in productivity. In emerging countries with mostly banking financial systems, bank-based financial inclusion is a significant enabler of financial inclusion, accelerating economic development through inclusive growth (Swamy, 2012). Over the last 10 years, there has been an explosion in the use of mobile payment systems. Because mobile phones have become so pervasive in people's everyday lives, they have also become an integral part of the way that people travel. It is crucial to have a variety of mobile payment methods available for tourists so that they may purchase products and services while they are traveling. Financial inclusion (FI) has been highlighted as a growth-promoting element for emerging nations. (Abubakar et al., 2020). According to (Girón et al., 2021), a greater degree of financial inclusion raises the amount of official savings in nations, which boosts their growth. The concept of financial inclusion reflects that the development of any economy is contingent on individuals from all socioeconomic levels having access to banking and other financial services. Over the past few decades, financial and banking regulators, governments, and academia have all paid close attention to financial inclusion. It is now one of the essential pillars of sustainable development. (Carrillo-Hidalgo and Pulido-Fernández, 2016; Qamruzzaman and Wei, 2019b).

As far as we know, most researchers concentrate on how tourism affects financial inclusion (Carrillo-Hidalgo and Pulido-Fernández, 2019b). Stated tourism is one of the most important weapons for assuring economic growth, improving the quality of life, and eliminating poverty and inequality in developing countries. This study examined the World Bank's role in inclusive tourism financing as a sustainable development strategy. Through a descriptive analysis of more than 92 projects in different fields, they found that the World Bank's tourism funding could benefit from a stronger emphasis on financial inclusion, allowing it to more efficiently and effectively achieve its goals of reducing poverty and fostering development (Panggabean and Sipahutar, 2019). Demonstrates how the tourism sector may promote economic growth by providing a range of job possibilities and generating foreign revenue in Indonesia, which is then utilized to stimulate other economic activities. They stated that tourism promotes the usability of local products and focuses on developing local communities, thus ensuring financial inclusion. Financial and social inclusion are impacted by tourism (Kumar et al., 2020).

Shi et al., (2020) claim that low-income families benefit greatly from gender-sensitive financial inclusion. Similarly, the economic

prosperity of low-income families in the regions around tourist locations benefits greatly from a tourism business that considers gender. The importance of financial inclusion in the growth of sustainable tourism is growing. Nonetheless, there are no studies examining the relationship between financial inclusion and the expansion of the tourism sector in the existing empirical research. However, very few works of literature concentrate on the opposing notion that it is essential to ensure financial inclusion to boost tourism. Financial inclusion's effect on tourist growth was studied (Shi et al., 2020) using data from 1995–2016 from 24 developed and 21 developing countries. The findings, which feature policy recommendations and useful ideas, demonstrate that financial inclusion has a major effect on various facets of tourism growth. The results also suggest that the impact is significantly magnified in emerging and developed markets (Carrillo-Hidalgo and Pulido-Fernández, 2016). Have proposed a technique for determining if the performance of International Financial Institutions regarding tourism financing is inclusive. Promoting financial inclusion is essential if tourism is a driver of economic growth. According to their research, while financial intermediaries fund governments and large businesses, none of these institutions' financing practices, financing volumes, or non-financial actions promote financial inclusion for the poor. Financial inclusion in sustainable wealth creation for developing and developed countries was studied using the GMM model (Gao et al., 2022). The results demonstrate that financial inclusion affects various elements that contribute to the expansion of China's tourism sector. Raising people's financial literacy and strengthening the security of technologically-based financial instruments are other effective means of facilitating financial inclusion. Promoting rural tourism may be seen as one of the most crucial factors in extending financial inclusion, alongside agricultural development (Singh, 2022). This article will investigate the factors that motivate financial inclusion and ensure long-term tourism development in Bangladesh. To that end, we hypothesize that the financial inclusion index—which measures factors including the availability, development, and performance of financial institutions and markets—has a salutary impact on the travel industry. This is because the elimination of credit and liquidity limitations for tourist sector players is a direct result of improved access to financial institutions and markets. Therefore, these parties may purchase tourism-related products and services at reduced costs.

H2Financial inclusion positively influences tourism development.

2.3 Good governance and tourism development

A country's tourism growth can be quantified using an index that considers both inbound and outbound tourist spending and the sector's contribution to total employment. Good governance is characterized by government efficiency, political stability, high-quality rules, the rule of law, citizen participation, and individual accountability (Khan et al., 2021). Governance aims to maintain a good relationship between the rulers and the ruled. Even though most academics interchangeably refer to both governance and good governance, good governance is crucial for accomplishing long-term development objectives. Accountability and transparency, the absence of violence and political stability, the efficacy of governmental policy, the eradication of corruption, the standard of governance, and

the formation of the rule of law are the six factors that support good governance in every community (Ali, 2015).

Shortly, governance will surely take center stage in the development and policy of tourism destinations. The findings of this research highlight the importance of using independent categorical variables to aid in the creation and evaluation of explanatory claims, the explanation of conceptual statements, and the promotion of comparative analysis and policy learning. Furthermore, it has established connections between the literature on governance in political science and public policy and the specific challenges faced by the tourism sector. The relationship between policy actors and steering modes, as well as the balance between state intervention and self-regulation, serve as the basis for the categorical variables in this study. The resulting matrix identifies four different governance systems, including hierarchies, markets, networks, and communities. Rather than occurring in a vacuum, tourism governance must be viewed as operating within particular frameworks or representations of governance (Hall, 2013).

Social capital, political capital, and their interplay determine the importance of governance and long-term tourism sustainability (Nunkoo, 2017). In contrast to neoclassical philosophy, which stresses and is limited to market links, good governance notions acknowledge the importance of non-market forces, such as local communities and civil society, to the development process. Governance frameworks encourage local communities and civil society, usually excluded from tourism policymaking, to participate in tourism planning as legitimate partners. The author concludes that trust and power should cooperate rather than act alone. The synergistic view of social capital can positively affect sustainable tourism development and governance by altering formal institutions and the rule of law.

(Khan et al., 2021) used data from the World Development Indicators (WDI) to demonstrate that governance favors tourism development and its constituent parts. Additionally, it is found that all governance metrics encourage the growth of the tourism industry. On the other hand, tourism in developing nations is severely harmed by terrorism, environmental degradation, and corruption. However, trade openness and tourism have a good association. The comparative study by (Daryaei et al., 2012) between OECD nations and developing countries reveals that the OECD countries are ahead of developing countries in various good governance indexes, which is the cause of the rising visitor numbers in these countries. A significant impact is created on the country's tourism industry's growth through strong governance established by the study.

To be effective, a set of tourism policies must be conceptually and thematically solid and founded on the realities of existing and forthcoming issues. The 2010 Bangladesh Tourism Policy, however, is not as well written. This study emphasizes the importance of the government's commitment to the development of the policy-motivated tourism industry in the country, with active participation from the private sector and non-profit organizations, as well as the training of tourism industry human resources to develop their skills in tourism policy-making, planning, and management. It is critical to stimulate both governmental and private sector investments in tourism infrastructure and services. The fundamental goal of Bangladesh's tourism strategy should be the expansion of innovation and entrepreneurship. Establishing a "Tourist Safety Force" as part of the country's law enforcement authorities and implementing zoning restrictions in environmentally sensitive areas

are key steps that can improve the sustainability and security of Bangladeshi tourism. Smart tourist policies are critical, but so are the skills and resources required to implement them. To compete with local and international competition, Bangladesh's tourism sector needs drastically strengthen its marketing and branding (Hassan and Kokkranikal, 2018).

Poor maintenance of the destination's environment and resources; inadequate tourist facilities, activities, and infrastructures; security and safety concerns; a lack of a dedicated cell or body to guarantee the quality of tourism products and services; a lack of coordination and partnership among tourism stakeholders; an ineffective marketing strategy; and an insufficient budget are all factors that slow down the development of tourism in Bangladesh as a whole (Muneem et al., 2020; Manigandan et al., 2022). Working cooperatively with 15 ministries, this strategy includes 11 sectors to cover. They also classified the nation's tourism into seven regions, each corresponding to a different local government division. After thorough research and a comparison of Bangladeshi and Bhutanese tourist policies, it was concluded that Bangladesh should adopt the "Low Volume, High Value" approach used by The Kingdom of Bhutan (Karim, 2014). H3Good governance accelerates tourism development

3 Data and methodology of the study

3.1 Theoretical development and model specification

Existing literature dealing with the determinants of tourism development, the present study intends to explore the effects of environmental sustainability, financial inclusion, and good governance on tourism development in Bangladesh. Based on the literature, the generalized relationship between ES, FI, GG, and TD, along with the control variables, is as follows:

$$TD \int ES, FI, GG, FDI, TO \quad (1)$$

With the mediating effects of clean energy, i.e. (ES*FI, GG*ES), the above equation has been enlarged and represented as follows:

$$TD \int ES, FI, GG, FDI, TO, (ES*FI), (ES*GG) \quad (2)$$

TD denotes tourism development, CE for clean energy, and ES explains environmental sustainability, FDI for foreign direct investment, GE for governmental effectiveness, and ED for education. Moreover, the mediating role of clean energy through ES and FDI on TD has been addressed with the inclusion of interactive terms. The above Eqs. 1, 2 can reproduce in the following manner after log operation.

$$TD_t = \alpha_0 + \beta_1 CE_t + \beta_2 ES_t + \beta_3 FDI_t + \beta_4 GE_t + \beta_5 ED_t \quad (3)$$

$$TD_t = \alpha_0 + \gamma_1 CE_t + \gamma_2 ES_t + \gamma_3 FDI_t + \gamma_4 (ES*CE) + \gamma_5 (FDI*CE) + \gamma_6 GE_t + \gamma_7 ED_t \quad (4)$$

Where α_0 is constant, the coefficient of $\beta_1 \dots \dots \dots \beta_5$ explain the relations of CE, ES, FDI, GE, and ED on tourism development. Furthermore, the interactive effects can be found with the coefficient of γ_4 and γ_5 .

3.2 Financial inclusion

According to existing literature, the measurement of financial inclusion in empirical assessment has revealed two lines of consideration. A group of researchers employed single proxies, and another considered the financial inclusion index with multiple proxies (Qamruzzaman and Wei, 2019a; 2019b; Chuc et al., 2021; Eggho and Bangakã, 2021). By following Sarma (2008), the study measured financial inclusion by constructing an index with the three aspects of financial inclusion, such as accessibility, availability, and financial service usage (see Table 1 for details proxies).

The study implemented Principal Component Analysis (PCA), which is widely utilized by, e.g., Jia et al., (2021); Qamruzzaman et al., (2021). The application of PCA is an effective and simple tool in reducing dimensions but retaining the properties of the original data set. The following Eq. 5 has been implemented for index development.

$$FII = \sum W_i FI_{it} \quad (5)$$

Where FII denotes the financial inclusion index, W_i for principal component weight, FI_{it} for financial inclusion value at t period. The results of PCA for variables selection with eigenvalue are displayed in Table 2, and factors for index construction report in Table 3, along with the coefficient score matrix.

3.3 Estimation strategy

3.3.1 Unit root test

It is essential to check the series utilized in the econometric model for stationarity if one wishes to guarantee reliable conclusions and avoid the risk of erroneous regression. Before examining the long-term dynamics, it is necessary to determine the correct integration sequence. To verify the presence of unit roots throughout the series that goes into the construction of our model, we resorted to two distinct methods. The research unit's properties in the time series assessment have played a pivotal role in selecting the appropriate econometrical techniques for deriving the coefficients of the explanatory variables (Meng et al., 2021). Following the existing literature, the study has performed several stationary tests, which are commonly known as the ADF test (Dickey and Fuller, 1979), the P=P test (Phillips and Perron, 1988), the DF-GLS test (Elliott et al., 1996), the KPSS test (Kwiatkowski et al., 1992).

3.4 Bayer-combined cointegration test

As a means of testing the null hypothesis of no cointegration relationship, we use the joint test statistics established by Bayer and Hanck (2013). The Engle and Granger test, the Johansen test, the Peter Boswijk test, and the Banajee test are all rolled into one new combined cointegration test. One of the numerous benefits of this strategy is that it may provide model-specific cointegration findings. The Bayer-Hanck test evaluated the level of significance associated with each cointegration equation using Fisher's formulas in the way described below.

$$EG - JOH = -2[LN(PEG) + LN(PJOH)]$$

$$EG - JOH - BO - BD = -2[LN(PEG) - \ln(PJPH) + \ln(PBO) + \ln(PBDM)]$$

TABLE 1 Variables definition and data sources.

Variables	Notation	Definition	Data sources
Remittances	<i>Rim</i>	Personal remittances received to GDP (%)	WDI World Bank, (2022)
Economic policy uncertainty	EPU	Economic Policy uncertainty index	Baker, Bloom, and Davis (2016)
Financial inclusion index (FII) Authors' construction with the following four proxies			
<i>ATMs per 100,000 adults</i>			World Development Indicator World Bank, (2022)
<i>Number of commercial bank branches per 100,000 adults</i>			
<i>Number of depositors from commercial banks per 1,000 adults</i>			
<i>Number of borrowers from commercial banks per 1,000 adults</i>			
Trade openness	TO	The sum of imports and export as a % of GDP	
Exchange rate	EX	Real exchange rate	

Note: WDI, for World Development Indicators.

TABLE 2 Results of PCA for financial inclusion index.

Principal components	Eigenvalue	Cumulative (%)	Eigenvalue	Cumulative (%)
	India		China	
Components-1	1.9452	.5942	1.7812	.7515
Components-2	.9845	.7925	.8641	.8451
Components-3	.8452	.8944	.5125	.9531
Components-4	.7954	1.000	.4481	1.0000

PEG, PJOH, PBO, and PBDM represent the probability of different model cointegration tests in Eqs. 6, 7. If the approximate Fisher statistic exceeds the criteria established by Bayer and Hanck (2013), we may conclude that cointegration exists. In addition to the Bayer and Hanck combined cointegration tests, the Johansen cointegration test is applied as a robustness check in a multivariate situation. The Johansen test determines the number of cointegrating vectors between variables. Cointegration cannot occur without each cointegrating vector. The Johansen et al. (1990) techniques consider calculating all feasible cointegrating vectors between the variables.

3.5 Autoregressive disoriented lagged (ARDL) and augmented-autoregressive disoriented lagged

To validate cointegration, the ARDL bound test was put to use in this investigation. This method uses either the Wald test or the joint F-statistic to determine whether the variables are cointegrated. Comparing the probability of cointegration with the likelihood that the model does not integrate yields some interesting insights. Only if the F-statistic is larger than the required upper limit would it be possible to reject the null hypothesis that there was no integration. Following M. Hashem Pesaran et al., (2001), the generalized ADRL model for the study was considered for detecting both long-run and short-run coefficients by performing the following equation.

$$\begin{aligned} \Delta \ln TD_t = & \alpha_0 + \sum_{i=1}^n \mu_1 \Delta \ln TD_{t-i} + \sum_{i=0}^n \mu_2 \Delta \ln CE_{t-i} + \sum_{i=0}^n \mu_3 \Delta \ln ES_{t-i} \\ & + \sum_{i=0}^n \mu_4 \Delta \ln FDI_t + \sum_{i=0}^n \mu_5 \Delta \ln GE_{t-i} + \sum_{i=0}^n \mu_6 \Delta \ln ED_{t-i} \\ & + \gamma_1 \ln TD_{t-1} + \gamma_2 \ln CE_{t-1} + \gamma_3 \ln ES_{t-1} + \gamma_4 \ln FDI_{t-1} \\ & + \gamma_5 \ln GE_{t-1} + \gamma_6 \ln ED_{t-1} + \omega_{1t} \end{aligned} \quad (6)$$

For interactive terms:

$$\begin{aligned} \Delta \ln TD_t = & \alpha_0 + \sum_{i=1}^n \mu_1 \Delta \ln TD_{t-i} + \sum_{i=0}^n \mu_2 \Delta \ln CE_{t-i} + \sum_{i=0}^n \mu_3 \Delta \ln ES_{t-i} \\ & + \sum_{i=0}^n \mu_4 \Delta \ln FDI_t + \sum_{i=0}^n \mu_5 \Delta \ln (ES^*CE)_{t-i} \\ & + \sum_{i=0}^n \mu_6 \Delta \ln (FDI^*CE)_t + \sum_{i=0}^n \mu_7 \Delta \ln GE_{t-i} + \sum_{i=0}^n \mu_8 \Delta \ln ED_{t-i} \\ & + \gamma_1 \ln TD_{t-1} + \gamma_2 \ln CE_{t-1} + \gamma_3 \ln ES_{t-1} + \gamma_4 \ln FDI_{t-1} \\ & + \gamma_5 \ln (ES^*CE)_{t-1} + \gamma_6 \ln (FDI^*CE) + \gamma_7 \ln GE_{t-1} \\ & + \gamma_8 \ln ED_{t-1} + \omega_{1t} \end{aligned} \quad (7)$$

3.6 Asymmetric autoregressive disoriented lagged estimation

In the recent literature, the application of asymmetric framework has been extensively used in effective policy

formulation (Lingyan et al., 2021; Xu et al., 2021; Li and Qamruzzaman, 2022b; Xia et al., 2022). Asymmetric framework assists in exploring the elasticity of explanatory variables through the decomposition that is positive and negative shocks, which reveals fresh evidence over the conventional relations. The study considered a non-linear framework following Shin et al., (2014a). The following generalized model is to be implemented. Where β^+ , β^- , γ^+ , γ^- , π^+ , and π^- for the long-run pavements. The coefficient of β^+ and β^- specifies the effect of positive and negative shocks in CE, ES and γ^+ and γ^- denotes the asymmetric effects of FDI on RE. Furthermore, the coefficients of δ_i measures the effects of control variables in the equation.

The asymmetric shock of financial inclusion, i.e., FI⁺; FI⁻, environmental sustainability, i.e., ES⁺; ES⁻ and Good Governance (GG⁺; GG⁻) can be derived in the following manner.

$$\begin{cases} POS(FI)_{1,t} = \sum_{k=1}^t \ln FI_k^+ = \sum_{k=1}^T \text{MAX}(\Delta \ln FI_k, 0) & POS(ES)_{1,t} = \sum_{k=1}^t \ln ES_k^+ = \sum_{k=1}^T \text{MAX}(\Delta \ln ES_k, 0) \\ NEG(FI)_t = \sum_{k=1}^t \ln FI_k^- = \sum_{k=1}^T \text{MIN}(\Delta \ln FI_k, 0) & NEG(ES)_t = \sum_{k=1}^t \ln ES_k^- = \sum_{k=1}^T \text{MIN}(\Delta \ln ES_k, 0) \end{cases}$$

$$\begin{cases} POS(GG)_{1,t} = \sum_{k=1}^t \ln GG_k^+ = \sum_{k=1}^T \text{MAX}(\Delta \ln GG_k, 0) \\ NEG(GG)_t = \sum_{k=1}^t \ln GG_k^- = \sum_{k=1}^T \text{MIN}(\Delta \ln GG_k, 0) \end{cases}$$

Now, Eq. 8 is transformed into asymmetric long-run and short-run coefficient assessment as follows:

$$\begin{aligned} \Delta TD_t = & \partial U_{t-1} + (\beta^+ FI_{1,t-1}^+ + \beta^- FI_{1,t-1}^-) + (\gamma^+ ES_{1,t-1}^+ + \gamma^- ES_{1,t-1}^-) \\ & + (\pi^+ GG_{1,t-1}^+ + \pi^- GG_{1,t-1}^-) + \delta X_{1,t-1}^* \sum_{j=1}^{m-1} \lambda_j \Delta TD_{t-j_0} \\ & + \sum_{j=1}^{n-1} (\pi^+ \Delta FI_{1,t-1}^+ + \pi^- \Delta FI_{1,t-1}^-) \\ & + \sum_{j=0}^{m-1} (\pi^+ \Delta ES_{1,t-1}^+ + \pi^- \Delta ED_{1,t-1}^-) \\ & + \sum_{j=0}^{m-1} (\beta^+ \Delta GG_{1,t-1}^+ + \beta^- \Delta GG_{1,t-1}^-) + \sum_{j=0}^{m-1} \mu \Delta X_{1,t-1}^* \varepsilon_t \end{aligned} \quad (8)$$

A standard Wald test will be performed using the null symmetry hypothesis to detect asymmetry over the long and short term. Only very small sample sizes can establish unequal long-term and short-term associations. Furthermore, if the test statistics are larger when compared to the critical value, then the asymmetric long-run cointegration that is to be tested by following F-bound testing, Joint Primality testing, and tBDM testing will be validated in the empirical model.

3.7 Fourier Toda and Yamamoto causality test

According to the existing literature, the conventional granger causality test offered by. Has misconception and failed to address the issue of structural changes in the data, thus producing spurious estimation in some instances. To overcome the limitation of conventional casualty tests, The Granger (1969) causality test was used by the research team to investigate the potential for causation between the various macroeconomic variables. However,

the Granger test and many other causality tests in the literature, including those by Toda and Yamamoto, overlook structural discontinuities in the series. This is the case even though the Granger test was developed (TY; (Toda and Yamamoto, 1995). Enders and Jones (2016) illustrated that problems with misspecification might arise in the VAR model if there is an inability to account for structural fractures. Consequently, there is an increased likelihood that the correct null hypothesis may be incorrectly rejected. Nazlioglu et al., (2011) created the Fourier TY causality tests to correct this deficiency with the expansion of the trigonometric term. The VAR model may be replicated in the following ways:

$$y_t = \alpha(t) + \beta_1 y_{t-1} + \dots + \beta_{p+d} y_{t-(p+d)} + \varepsilon_t \quad (9)$$

$$y_t = \alpha(t) + \beta_1 y_{t-1} + \dots + \beta_{p+d} y_{t-(p+d)} + \vartheta_1 \sin \frac{2k\pi t}{T} + \vartheta_2 \cos \frac{2k\pi t}{T} + \varepsilon_t \quad (10)$$

The null hypothesis for Fourier-TY test is no causality between variables ($H_0: \beta_1 = \beta_2 \dots \dots \dots \beta_p = 0$)

4 Results and interpretation

4.1 Unit root test

Econometric empirical nexus assessment with time series data demands detecting variables' static properties in selecting the appropriate econometrical techniques for efficient and consistent estimation. The study has implemented several unit root tests, such as the ADF test, which is familiarized by Dickey and Fuller (1979), the GF-DLS test, which is offered by Elliott et al. (1996), and the PP test, which is introduced by -Phillips and Perron (1988), in documenting the stationary attributes of the research data set with the null hypothesis of not stationary and for KPSS-Kwiatkowski et al. (1992) with the null of stationary. Table 4 exhibited the results of the stationary test and established that all the variables are stationary after the first difference, and neither has exposed stationary after the second difference.

The study has extended the unit root test with the implementation of the second-generation unit root test announced by Ng and Perron (2001), and the results are displayed in Table 5. In terms of test statistics, that is MZa, MZt, MSB, and MPT derived from estimation, and it is apparent that all the test statistics are statistically significant at a 5% significance level, indicating the variables are stationary after the first difference.

The following study implemented the novel combined cointegration test, introduced by Bayer and Hanck (2013), with the integration of the existing conventional cointegration test in authenticating the long-run association between tourism development, financial inclusion, good governance, and environmental quality in Bangladesh. Table 6 exhibits the results of the cointegration test. Refers to the test statistics, it is manifested that the null hypothesis of no-cointegration is rejected in all model assessments; alternatively, the study establishes a long-run association between tourism and explanatory variables.

Next, the study assesses the long-run cointegration by implementing the linear framework proposed by M Hashem

TABLE 3 Results of Components score coefficient matrix.

Financial inclusion index proxies ¹	Factor score coefficient	
	India	China
FI ₁	.6845	.5548
FI ₂	.4533	.4591
FI ₃	.5214	.4655
FI ₄	.4112	.3512

Pesaran and Smith (1995) and further developed by M. Hashem Pesaran et al. (2001) and the non-linear framework offered by Shin et al. (2014a). The results of the long-run cointegration test under the symmetric and asymmetric framework are available in Table 7. The test statistics derived from the symmetric (asymmetric) assessment that is $F_{overall} = 11.203$ (12.062), $t_{DV} = -5.69$ (-4.857), and $F_{IDV} = 8.688$ (8.761) revealed statistically significant at 1% level, indicating the rejection of the null hypothesis of no-cointegration. Study findings suggest long-run association under the symmetric and asymmetric framework environment. In the following section, the study evaluates the explanatory variables magnitudes on

tourism development under a symmetric and asymmetric framework.

4.1.1 For long-run symmetric assessment

The results of long-run coefficients of symmetric assessment displayed in Table 8. The study documented a negative and statistically significant linkage between the nexus between environmental quality, measured by carbon emission, and tourism development (a coefficient of -0.1347). Study findings postulated that environmental degradation has adverse effects on tourism development; precisely, a 10% growth in carbon emission will result in a decline in tourism progress by 1.347%. The existing literature supports the findings of an adverse association between environmental quality and tourism development (Green and Hunter, 1992). For good governance (a coefficient of 0.01625). The study unveiled a positive and statistically significant linkage to tourism in Bangladesh. More precisely, a 10% development in governmental effectiveness will result in tourism development by 0.1625% , indicating that governmental effectiveness is a thriving factor in tourism development. Our findings align with existing literature (Detotto et al., 2021; Hassan and Meyer, 2022; Yang et al., 2022). The positive and statistically significant tie between financial inclusion and tourism development explained that financial inclusion accelerated the present status of tourism

TABLE 4 Results of unit root test.

	At level				After first difference			
	ADF	GF-DLS	PP	KPSS	ADF	GF-DLS	PP	KPSS
<i>For Brazil</i>								
TOR	−.2573	−1.715	−1.8856	.7984***	−6.7477***	−5.4954***	−7.9486***	.0207
FI	−.9351	−.5654	−1.4497	.7395***	−8.7373***	−7.2702***	−5.6356***	.0188
IQ	−.4616	−1.9925	−1.6997	.8669***	−8.0435***	−5.5837***	−8.3038***	.0213
EQ	−1.3845	−.5183	−1.7074	.802***	−7.7193***	−7.8388***	−6.275***	.0195
TO	−.4214	−2.2674	−2.4592	.7112***	−8.617***	−9.472***	−5.9688***	.0194
FDI	−1.7206	−1.6411	−1.414	.7085***	−7.2408***	−8.4006***	−5.3874***	.0203

TABLE 5 Results of Ng-Perron unit root test.

	At level					At first difference			
	MZa	MZt	MSB	MPT		MZa	MZt	MSB	MPT
TOR	−1.792	−1.1962	.3057	7.8258		−24.6637	−4.1101	.1567	5.1232
FI	−2.6277	−1.0496	.3479	7.888		−21.8082	−4.5576	.1442	3.3834
IQ	−1.9655	−1.733	.2914	8.6769		−18.4287	−4.7	.1292	4.6921
EQ	−2.0994	−.8912	.3569	8.6497		−19.6062	−5.5902	.1534	3.7751
TO	−2.0167	−1.7	.3193	7.6499		−19.8258	−4.5359	.1591	3.5683
FDI	−1.7075	−.7233	.3155	8.7107		−17.1099	−4.925	.1456	4.6622
Asymptotic critical values: Ng and Perron (2001), table 1					1%	−23.8	−3.42	.143	4.03
					5%	−17.3	−2.91	.168	5.48
					10%	−14.2	−2.62	.185	6.67

TABLE 6 Results of combined cointegration test.

Model	EG-JOH		EG-JOH-BO-BDM	
	Statistics	CV	Statistics	CV
$TOR = \int FI$	14.744	11.229	36.861	21.931
$TOR = \int FI, GG$	10.928	10.895	24.468	21.106
$TOR = \int FI, GG, EQ$	11.259	10.637	24.142	20.486
$TOR = \int FI, GG, EQ, FDI$	10.774	10.576	21.325	20.143
$TOR = \int FI, GG, EQ, FDI, TO$	10.774	10.419	20.935	19.888

TABLE 7 Results of long-run cointegration-linear and non-linear framework.

Approach	Model	$F_{overall}$	t_{DV}	F_{IDV}
ARDL	$TOR \int FI, GG, EQ, FDI, TO$	11.203***	-5.69***	8.688***
Non-Linear ARDL	$TOR \int FI^+, FI^-, GG^+, GG^-, EQ^+, EQ^-, FDI, TO$	12.062***	-4.857***	8.76***

development. According to financial inclusion elasticity, it is assumed that a 10% growth in financial inclusion, that is, access to financial services, will boost tourism development by 1.0173%. A study suggests that financial services.

4.1.2 For long-run asymmetric assessment

Table 9 exhibited the results of asymmetric coefficients for the long-run and short-run assessment. The study has implemented the standard Wald test in assessing the asymmetric association between independent variables, including environmental sustainably, good governance, financial inclusion, and tourism development, with a null hypothesis of symmetric association. Concerning the test statistics, ($W_{LR}^{ES} = 6.631$; $W_{LR}^{GG} = 7.224$; and $W_{LR}^{FI} = 12.145$), all the test statistics are statistically significant at a 1% level, confirming the asymmetric association between target variables and tourism development.

The asymmetric shocks that are positive and negative innovation in environmental quality, more precisely increases (decreases) carbon emission in the ecosystem, has revealed a negative (negative) linkage with tourism development, indicating that environmental degradation and adversity deteriorate the speed of tourism development. In particular, a 10% increase (decrease) in carbon emission results in degradation (development) in tourism development by .5491% (1.3639%), suggesting that environmental protection for ecologically balanced offer a conducive ambiance for tourism development. According to the asymmetric coefficients of good governance, measured by governmental effectiveness, positive (negative) variations in good governance established a positive (positive) connection with tourism development, implying that attracting international tourists for tourism development is essential to offer stability to the economy. Particularly, a 10% development (degradation) of governmental effectiveness results in tourism development (degradation) by 1.2687% (1.3431%); in terms of the

asymmetric nexus between financial inclusion and tourism development, the study disclosed a positive, statistically significant association between them. Specifically, 10% positive (negative) innovations in financial inclusion augmented (reduced) the movement of tourism development by .3077% (.6369%). Study findings suggest that expansion of financial services in the financial system opens an avenue to get financial services and benefits with ease; the access to financial services prompts financial image in the mind of international tourists, eventually leading to tourism development.

The study has implemented the standard Wald test in assessing an asymmetric association between independent variables, including environmental sustainably, good governance, financial inclusion, and tourism development, with a null hypothesis of symmetric association. Concerning the test statistics, it is apparent that all the test statistics are statistically significant at a 1% level, indicating the confirmation of asymmetric association between target variables and tourism development.

4.1.3 Short-run symmetric assessment

Refers to the short-run elasticities of the independent variables, the study documented adverse effects running from carbon emission to tourism development (a coefficient of -.1039), positive influences from good governance (a coefficient of .0162), and financial inclusion (a coefficient of .1017) and all the coefficient are statistically significant at a 1% level. Study findings suggest that tourism development in Bangladesh will experience development due to a 1% change in carbon emission by -.1039%, good governance accelerates by .0162%, and financial inclusion prompts by .1017%, respectively. The error correction term revealed negative statistically significant (a coefficient of -.3841), explaining the correction of disequilibrium due to shocks in the short-run at a speed of 38.41% per year; alternatively, the long-run equilibrium can be reached in 2.603 years.

TABLE 8 Results of long-run coefficients: symmetric and asymmetric assessment.

	Symmetric assessment			Asymmetric assessment		
	Coefficient	t-stat	Std. error	Coefficient	t-stat	Std. error
EQ	-.1347	.004255	-31.6282			
EQ ⁺				-.05491	.010802	-5.08313
EQ ⁻				-.13639	.010038	-13.5878
GG	.0162	.002597	6.25864459			
GG ⁺				.12687	.005463	23.22352
GG ⁻				.134313	.004621	29.06574
FI	.1017	.003354	29.84713775			
FI ⁺				.03077	.00477	6.4508
FI ⁻				.06369	.01191	5.3459
FDI	.0672	.0025	25.9764	.07555	.00308	25.1183
FD	.0879	.00918	9.6296	.051848	.006639	7.80961
W_{LR}^{ES}				6.631		
W_{LR}^{GG}				7.224		
W_{LR}^{FI}				12.145		

4.1.4 Short-run asymmetric assessment

A short-run asymmetric association between independent variables, including environmental sustainability, good governance, financial inclusion, and tourism development with a null hypothesis of symmetric association, has been investigated using the standard Wald test. For the test statistics, ($W_{SR}^{ES} = 11.531$; $W_{SR}^{GG} = 10.656$; and $W_{SR}^{FI} = 8.9413$), it is apparent that all the test statistics are statistically significant at a 1% level, indicating the validation of an asymmetric association between target variables and tourism development. The error correction term was negative and statistically significant (a coefficient of -0.1608), implying the long-run disequilibrium to be corrected at a speed of 16.08% per year.

Inferring the elasticity of carbon emission on tourism development, the study established asymmetric shocks of environmental sustainability negatively tied with tourism development, and the coefficients are statistically significant. Additionally, the asymmetric coefficients of governmental effectiveness unveiled a positive and statistically significant association with tourism development in Bangladesh. The asymmetric variation of financial inclusion established a similar vine of relations like governmental effectiveness.

4.2 The mediating role of financial inclusion and good governance through environmental sustainability

Next, we moved the empirical investigation with the inclusion of interactive terms for investigating the mediating effects of financial inclusion and good governance. The result of the symmetric, asymmetric assessment with interactive terms is displayed, in Table 10. For symmetric assessment, the coefficient of interactive term between environmental sustainability and good governance (a coefficient

of 0.0917) and environmental sustainability and financial inclusion (a coefficient of 0.0322) have revealed positive and statistically significant, suggesting the mediating role of good governance and financial inclusion. In terms of asymmetric assessment, the study exposed the asymmetric innovation in interactive terms, that is, the positive and negative variations revealed positively associated with tourism development, especially in the long run.

4.3 Causality test

To document the long-run causal association, the study implemented the non-granger causality test following. The result of the causality test is displayed in Table 11. The study has implemented the non-granger causality framework offered by Toda and Yamamoto (1995) for directional causal assessment, and the results are displayed in Table 11. According to the test statistic from causal assessment, the study documented two vain of association that is bidirectional and unidirectional. For bidirectional causal effects, the study established feedback hypothesis holds in explaining the causal relations between tourism development and good governance ($TOR \leftarrow \rightarrow GG$); tourism development and environmental sustainability ($TOR \leftarrow \rightarrow ES$); financial inclusion and tourism development ($FI \leftarrow \rightarrow TOR$). Furthermore, the study unveils unidirectional causality running from foreign direct investment to tourism development ($FDI \rightarrow TOR$) and tourism-led financial development ($TOR \rightarrow FD$).

4.4 Robustness test

The study implemented Dynamic OLS, Fully modified OLS, and CCR regression to evaluate the empirical model construction

TABLE 9 Results of short-run coefficients: symmetric and asymmetric assessment.

	Symmetric assessment			Asymmetric assessment		
	Coefficient	Std.error	T-stat	Coefficient	Std.error	T-stat
EQ	−.1039	.010994	−9.4571			
ES ⁺				−.0501	.0052	
ES [−]				−.0335	.0079	
GG	.1072	.0053	20.1615			
GG ⁺				.0169	.0046	3.6739
GG [−]				.0454	.0078	5.8205
FI	.0817	.0033	24.6158			
FI ⁺				.0467	.0076	6.1447
Fi [−]				.0423	.0039	10.8461
FDI	.0220	.0089	2.4709	.0107	.0065	1.6461
FD	.0710	.0053	13.2711	.0066	.0104	.6346
ECT (−1)	−.3841	.0388	−9.899	−.1608	.002632	−61.0946
Constant	−6.280786	.5007	−12.5440	−1.24555	1.0423	−1.1951
W_{SR}^{ES}				11.531		
W_{SR}^{GG}				10.656		
W_{SR}^{FI}				8.9413		
x_{Auto}^2	.869			.618		
x_{Het}^2	.655			.836		
x_{Nor}^2	.692			.789		
x_{RESET}^2	.513			.72		
CUSUM	Stable			Stable		
CUSUM Of Square	Stable			Stable		

consistency and efficiency in estimation. Table 12 exhibited the results of the robustness assessment. According to the sign of the study explanatory variables, the estimation confirmed the same vine of association between explanatory variables: environmental sustainability, financial inclusion, good governance, and tourism development. More specifically, good governance and financial inclusion are positively associated, and carbon emission reveals an adverse tie with tourism development, which aligns with symmetric and asymmetric estimation assessment.

5 Discussion

The study documented a negative and statistically significant linkage between environmental sustainability and tourism development, implying that carbon emission adversely causes tourism development. In terms of symmetric (asymmetric) investigation, the study suggested that a 1% reduction in carbon emission positively affects tourism development by .1039% (.0335%). The study advocated that a controlled environment

through carbon emission reduction can contribute to tourism. Our findings align with the existing literature (Ahmed and Laijun, 2014; Tong et al., 2022). Geographical aspects some physical factors, for instance, the location's geography and climate, the amenities offered there, and the marketing and advertising campaigns run by the tourism industry, affect the decisions that travelers make. However, it is vital to maintain the natural environment tourists visit, including natural habitats and local wildlife that is sometimes unique worldwide. As a result, a portion of tourist earnings is used to conserve the visited basic biological ecosystems. Pollution can reduce the appeal of natural elements such as stunning landscapes, natural hydrologic systems, clean water, pure air, and animal variety (Gössling et al., 2013). The competitiveness of most types of tourist destinations depends on maintaining a high degree of overall environmental quality, making it a top priority for destination management. There are many countries around the world where tourism generates significant revenue. The most visited tourist destinations of the world have one feature in common that sets them apart from other destinations: cleanliness. (Alam et al., 2022b).

TABLE 10 Results of Mediation assessment.

Long-run cointegration							
		$F_{overall}$	t_{DV}	F_{IDV}			
ARDL		14.222***	-5.712***	6.644***			
NARDL		6.394***	-5.236***	7.501***			
Panel –B: Long-run coefficients							
	Coefficient	t-stat	Std.error		Coefficient	t-stat	Std.error
LONG RUN							
EQ	.022702	.002999	7.569857	EQ ⁺	.028658	.010834	2.645191
GG	-.10091	.007838	-12.8749	EQ ⁻	.04785	.011707	4.087281
FI	.05114	.009504	5.380882	GG ⁺	-.12962	.003482	-37.2246
FDI	.106394	.003534	30.10591	GG ⁻	-.09212	.011945	-7.71192
FD	.094855	.006539	14.50599	FI ⁺	.064228	.002442	26.30147
				Fi ⁻	.036994	.004128	8.961725
				FI*ES	.056853	.007251	7.840712
				GG*ES	.071946	.011382	6.321033
				FI*ES	.075048	.010955	6.850571
				FI*ES	.051158	.005525	9.259367
GG*ES	.09178	.005734	16.00635	FDI	.027847	.011136	2.500629
FI*ES	.032221	.007164	4.497613	FD	.069324	.007033	9.85696
C	-.09542	.007173	-13.3032	C	-.0658	.002232	-29.4821
W_{LR}^{ES}					3.851		
W_{LR}^{GG}					6.525		
W_{LR}^{FI}					5.489		
$W_{LR}^{ES\ GG}$					12.882		
$W_{LR}^{ES\ FI}$					13.656		
Panel –C: Short-run coefficient							
EQ	.0289	.0097	2.9793	EQ ⁺	-.0185	.0106	-1.7452
GG	.0338	.0051	6.6274	EQ ⁻	-.0587	.0028	-20.9642
FI	.0249	.0024	10.375	GG ⁺	.015	.0094	-1.5957
FDI	.0919	.0103	8.9223	GG ⁻	.0337	.0083	-4.0602
FD	.0108	.0025	4.32	FI ⁺	.0158	.0096	1.6458
				Fi ⁻	.0455	.0038	11.9736
				FI*ES ⁺	.0039	.0056	.6964
				GG*ES ⁻	.0057	.0032	1.7812
				FI*ES ⁺	.0176	.0089	1.9775
GG*ES	.0103	.0042	2.4523	FI*ES ⁻	.026	.0092	2.826
FI*ES	.0956	.0115	8.313	FDI	.01	.0059	1.6949
				FD	-.24805	.002695	-92.0419

(Continued on following page)

TABLE 10 (Continued) Results of Mediation assessment.

Long-run cointegration							
		$F_{overall}$	t_{DV}	F_{IDV}			
Short-run symmetry test							
W_{SR}^{ES}					8.786		
W_{SR}^{GG}					11.952		
W_{SR}^{FI}					5.511		
$W_{SR}^{ES\rightarrow GG}$					5.452		
$W_{SR}^{ES\rightarrow FI}$					4.777		
Residual Diagnostic test							
χ^2_{Auto}	.582				.672		
χ^2_{Het}	.746				.715		
χ^2_{Nor}	.891				.611		
χ^2_{RESET}	.698				.672		

TABLE 11 Results of the Toda-Yamamoto casualty test.

	TOR	GG	EQ	FI	FDI	FD	Causalities
TOR		6.744*	10.748***	7.186*	10.931***	5.553	GG $\leftrightarrow$ TOR; ES $\leftrightarrow$ TOR; FI $\leftrightarrow$ TOR; FDI $\rightarrow$ TOR; TOR $\rightarrow$ FD; ES $\rightarrow$ GG; FDI $\rightarrow$ GG; FD $\rightarrow$ GG; ES $\rightarrow$ FDI; FDI $\rightarrow$ FI
GG	7.048*		6.592*	3.156	10.337***	9.615**	
EQ	8.944**	1.143		0.5	4.637	9.201**	
FI	9.867**	7.18*	1.484		7.914*	4.73	
FDI	2.206	5.493	7.242*	2.125		2.613	
FD	6.419*	5.458	3.26	1.528	1.624		

TABLE 12 Results of the coefficients robustness test.

Variables	OLS			Fully-modified OLS			CCR		
	Coefficient	Std	t-stat	Coefficient	Std	t-stat	Coefficient	Std	t-stat
FI	.1063	.0509	2.0884	.1246	.0605	2.0595	.1379	.0254	5.4291
ES	-.1714	.0772	-2.2202	-.1844	.0365	-5.052	-.1816	.0212	-8.566
GG	.1102	.0237	4.6497	.1684	.0991	1.6992	.1478	.0546	2.7069
FDI	.0842	.0689	1.222	.047	.0115	4.0869	.0862	.095	.9073
FD	.1431	.0837	1.7096	.073	.0121	6.033	.1804	.0195	9.2512

Our study findings established a positive and statistically significant association between financial inclusion and tourism development, validated under both symmetric and asymmetric assessment. Study findings advocate that easy access to financial services offers efficiency in a financial settlement, especially in the

case of currency conversion and electronic money transfer in rendering tourism services. The study findings are supported by the literature such as (Shi et al., 2020; Gopalan and Khalid, 2022; Xia et al., 2022). Innovation and financial inclusion are closely intertwined. Increased financial inclusion fosters greater levels of

firm innovation. The tourism industry is getting increasingly competitive; therefore, businesses must provide innovative goods and services. The ability of these businesses to innovate and provide better customer service can therefore be improved by expanding financial inclusion. The rise of promising entrepreneurs in the economy ensures development in the tourism sector. To meet their capital needs, entrepreneurs depend on the financial service industry. Increased access to financial services can stimulate entrepreneurial endeavors. Financial inclusion can promote enterprise growth and a culture of entrepreneurship in the tourism industry, resulting in increased supply and demand for tourism services. From the tourist's standpoint, a higher level of financial inclusion is crucial in the destination. The presence of banks and ATMs are fundamental financial services that contribute to the expansion of tourism (Qamruzzaman and Wei, 2019b; Yang et al., 2021). Increasing the accessibility and utilization of financial services could help provide the right environment for generating higher domestic tourism spending by attracting more tourists and stimulating domestic travel and tourism consumption. Increased financial inclusion can also reduce the tourism industry's excessive risk through the availability and accessibility of insurance and hedging alternatives. Financial inclusion is crucial to enhancing both local and international tourism. As a result, the nation's policymakers should focus on building a strong and resilient financial services industry (Singh, 2022).

Good governance revealed a positive and statistically significant linkage with tourism development in the long-run and short-run assessment under a linear framework. Furthermore, asymmetric assessment established that asymmetric shocks of good governance are positively tied to long-term and short-term tourism development. Our findings align with the existing literature (Kazemian et al., 2021; Khanna and Sharma, 2021; Mishra et al., 2021; Li and Qamruzzaman, 2022a). A country's ability to attract visitors and generate tourism revenue affects its government's standards. The fact that the results are compatible with not just one but two main hypotheses is an important finding. According to theoretical research findings in the tourism industry, offering high-quality public services and amenities is crucial in luring tourists. Second, the quantity of money spent by foreign tourists is positively impacted by the public's confidence in the government's ability to implement policies that promote the growth of the private sector. Good governance is when a government performs all of its duties without corruption or discrimination and within the bounds of the law (Daryaei et al., 2012; Phong, 2014). In every type of planning and decision-making, public institutions, the commercial sector, other civil society organizations, and individuals maintain the right process, method, and management. Good governance is a positive indicator of a nation's health and improves citizens' quality of life (Detotto et al., 2021). The traveler also favors visiting a nation with an effective government. It has been demonstrated by various researchers that the development of tourism and good governance indicators are positively correlated (Gao et al., 2022). The traveler wishes to go to a nation where fighting corruption and fostering economic progress is more successful. Traveling to a nation that upholds correct laws and regulations makes them feel safer and more

protected (Carrillo-Hidalgo and Pulido-Fernández, 2019a). For instance, Sri Lanka, a country with a significant tourism industry, is going through its worst period due to poor governance.

6 Conclusion and policy suggestions

Tourism-led economic growth has postulated the importance of tourism for economic growth. On the other hand, the adverse effects of tourism, especially on the environment, also have an assessment. However, the study's imputes is to investigate the effects of carbon emission, good governance, and financial inclusion on tourism development in Bangladesh. The long-run and short-run coefficients of environmental sustainability, financial inclusion, and good governance on tourism development has documented through the execution of ARDL (Pesaran et al., 2001) and non-linear ARDL (Shin et al., 2014b). Furthermore, the directional association assess by employing the Fourier TY casualty test.

According to the study findings, it is apparent that environmental sustainability is carbon emission negatively associated with tourism development both in the long-run and short-run assessment. Whereas the positive linkage revealed between financial inclusions, good governance, and tourism development, suggesting easy access to financial services in the financial system and governmental effectiveness act as a catalyst in augmenting tourism development's force. The asymmetric investigation established non-linearity in the empirical model for the long and short-run. In terms of asymmetric coefficients, the study unveiled the positive and negative shocks of environmental sustainability exposed negatively and statistically significant. In contrast, the asymmetric shocks of financial inclusion and good governance established positive and statistically significant Bangladesh tourism development in the long and short-run. The directional causality assessment revealed bidirectional causality running between explanatory variables to tourism development.

Based on the study findings, the following suggestions have focused on further development in Bangladesh tourism. First, the control of environmental adversity has revealed a positive tie with tourism, indicating that reducing carbon emissions in the ecosystem might accelerate tourism contribution. This study advocated environmental policy formulation and effective implementation for reducing carbon emissions into the environment. Second, an effective institution offers a conducive ambiance for business growth. For sustainable growth in the tourism industry, it is imperative to have governmental effectiveness so that international tourists feel confident in their decision to visit. Third, efficient financial intermediation allows easy access to avail financial services by the citizen. Furthermore, the accessibility of existing financial services also entices international tourists to visit the country.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: World development Indicator, International financial statistics.

Author contributions

YI: Conceptualization: Literature Survey: First Draft Preparation. PM: Conceptualization: Literature Survey: Methodology. NF: Data Collection: Literature Survey: First Draft Preparation. MQ: Data Collection, Methodology; Investigation.

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Climate risk and precautionary cash holdings: Evidence from Chinese listed companies

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Using Chinese listed companies as the research setting, this study investigates the impact of climate risk on corporate precautionary cash holdings and further explores possible underlying channels. We first apply the text mining technique to construct the climate risk indicator. The regression results then show that climate risk has a significant and positive impact on corporate precautionary cash holdings. Such positive relationship is stronger for firms with small size and those located in central and eastern China. Further mechanism analysis indicates that risk taking and external financing play a mediating effect between climate risk and corporate precautionary cash holdings. Our findings have important practical implications for companies to make sustainability strategies against potential climate risks.

KEYWORDS

climate risk, precautionary cash holdings, text mining, risk taking, external financing, panel regression model

1 Introduction

Climate risk should be highly concerned for it bringing increasing uncertainty to companies (Huang et al., 2018; Pinkse and Gasbarro, 2019; Kanagaretnam et al., 2022). Extreme weather events accelerate the depreciation of fixed assets of companies, even cause serious damage, and it also reduce labor productivity and adversely affect the sales and profitability of companies (Fuss, 2016; Hasegawa et al., 2016). From 2000 to 2019, there were more than 11,000 extreme weather events in the world, which directly caused 475,000 deaths and 2.56 trillion US dollars in economic losses (Eckstein et al., 2021). More importantly, in the process to a low-carbon economy, the climate risk causes that companies are negatively affected in finance and reputation because of changes in the aspects of relevant policies, laws, technologies and market (Huynh and Xia, 2021; Ren et al., 2021). For example, the transition of energy sources leads to that the utilization rate of traditional fossil energy declines, substantial financial and technical support are required for utilizing and developing renewable energy, and fossil fuel companies and energy intensive companies relying on fossil fuels face difficulties (Green and Newman, 2017; Zhang et al., 2022).

Climate risk not only brings uncertainty to companies, but also requires companies to implement appropriate risk prevention measures (Desing and Widmer, 2021). According to the preventive motivation theory, increasing precautionary cash holdings is an effective way to mitigate the uncertainty risks faced by companies (Han and Qiu, 2007). Precautionary cash can protect and buffer corporate investment and financing when companies face uncertainty. In terms of corporate investment, uncertainty increases the investment risk, thus corporate managers are more cautious about investment to reduce risks (Aghion et al., 2005; Bloom et al., 2007; Chatjuthamard et al., 2020). Cautious companies increase their precautionary cash holdings in order to meet future investment opportunities and reduce future financial distress (Bates et al., 2009). In terms of corporate finance, uncertain risks exacerbate information

asymmetry. To reduce market and default risk, banks often reduce the scale of loans to companies or even suspend related business transactions, which causes a reduction in external financing of companies (Salas and Saurina, 2002). In order to mitigate the negative impact of the decline of external financing, companies tend to increase cash savings to ensure liquidity (Bliss et al., 2015). In addition, the dynamic trade-off theory shows that companies need to weigh between current investment and financing and future ones when facing future financing constraints (Almeida et al., 2004). When faced with external financing pressures, it is more expensive for a company to raise external funds than to use internal funds. At this point, it may be the best option for companies to hold some precautionary cash to meet the needs of investment (Opler et al., 1999).

Concern over the impact of climate risk on companies has grown over the past few years, and existing researches mainly focus on the direct impact of climate risk on corporate operation. For example, Hong et al., (2019) points out that climate change aggravates natural disasters, which causes serious damage to companies' production and profits. Javadi and Masum (2021) found that the interest margin of bank loans paid by companies is significantly higher in areas with high climate risk. However, there are few studies about how companies strategically prevent climate risks, especially in China. In recent years, extreme weather events have occurred frequently in China, causing huge losses of economy. For example, the Wenchuan earthquake in 2008, the torrential rain in Beijing in 2012, the Typhoon Lichma in 2019 and the torrential rain in Henan in 2021 directly caused economic losses of 845.14 billion yuan, 11.64 billion yuan, 51.53 billion yuan and 114.269 billion yuan respectively. Moreover, as the largest carbon emitter globally, how to deal with the transformation risk is a major issue which is widely concerned by government, companies and the public (Tian et al., 2022a; Liu et al., 2022; Zhai et al., 2022). Therefore, this study is pioneering, which enriches research on precautionary cash holdings strategy adopted by Chinese listed companies to deal with climate risk. And Chinese listed companies pay close attention to climate risk, which provides an ideal research background.

Climate risk increases the uncertainty faced by companies (Barnett et al., 2020) and affects corporate strategies for cash holding. In the relevant research on influencing factors of corporate cash holdings, precautionary motivation, agency cost, transaction demand, and tax cost are all considered possible reasons for companies to maintain a high level of cash holdings (Bates et al., 2009). Among them, precautionary motivation is an important reason for companies to maintain a high level of cash holdings (Duchin, 2010; Mclean, 2011). This is because holding cash may help companies to better cope with liquidity risk and prevent operation uncertainty. As an important corporate operation decision, cash holding is affected by internal and external comprehensive factors of the company (Opler et al., 1999). Baum et al. (2009) and Pinkowitz et al. (2013) have studied the impact of macroeconomic fluctuations on corporate cash holdings. Others studied the impact of characteristics at the company level on cash holdings, such as company size, financial leverage, investment opportunities, ownership, and governance factors (Ferreira and Vilela, 2004; Ozkan and Ozkan, 2004; Kusnadi, 2011). However, most of the studies mentioned above focus on company the economic environment-level characteristics and discuss the impact of economic and internal factors on corporate cash holding strategies. The research on how climate risk affects corporate cash holdings is still

insufficient. And this study explores the impact of climate risk on corporate precautionary cash holdings.

In this study, we investigate whether and how climate risk affects precautionary cash holdings with the data of Chinese listed companies during the period 2007–2020. Text mining is used to construct climate risk perception indexes to represent the climate risk faced by companies. And we use panel regression model and mediator model to test the impact of climate risk on precautionary cash holdings. According to the empirical analysis, the following three conclusions are drawn: 1) Climate risk has a positive impact on precautionary cash holdings. And the higher climate risk companies face, the more precautionary cash holdings companies hold. This conclusion remains valid under a series of robustness tests. 2) The positive impact of climate risk on the precautionary cash holdings is stronger for firms with small scale and those located in central and eastern China. 3) Risk taking and external financing are two important channels for climate risk to affect precautionary cash holdings.

This study contributes to the existing literature in at least three ways: First, the climate risk index constructed in our research provides a practical method for studying the impact of climate risk on companies (Huang et al., 2018; Kanagaretnam et al., 2022). The climate risk measurement index used in most existing literature is the Global Climate Risk index (CRI) prepared by German. Although this index can describe the climate risks among different countries, it lacks climate information in company level, which is difficult to quantify the relationship between climate risks and companies (Ren et al., 2022). Thus, we use text mining technology in the corporate management discussion and analysis (MD&A) disclosure to construct the corporate climate risk perception index which measures the climate risk faced by the companies. By this measurement, we can estimate the impact of climate risk on companies more accurately with a larger research sample. Moreover, our study extends the field of text mining using MD&A (Choi et al., 2020; Tian et al., 2022b). Second, this study enriches the research about the influence channels of climate risk on precautionary cash holdings (Chen et al., 2020; Xiao et al., 2020). We find that risk taking and external financing are two important channels for climate risk to affect precautionary cash holdings. When facing high climate risk, on the one hand, corporate managers are usually cautious about investment to reduce risk taking, and thus increase precautionary cash holdings; On the other hand, as banks reduce the supply of loans, the scale of corporate external financing decreases, which also result in the increase of precautionary cash holdings. Third, this study supplements the important factors affecting corporate cash holding behavior. Previous studies explain the level of cash holdings based on the characteristics of economic environment and company level (Ferreira and Vilela, 2004; Ozkan and Ozkan, 2004; Baum et al., 2009; Kusnadi, 2011; Pinkowitz et al., 2013). Compared with these studies, our study also provides additional evidence that climate risk affects corporate cash holdings. And our findings have important implications for companies to deal with climate risks with prevention behaviors.

2 Theory and hypothesis

Climate risk greatly increases the uncertainty faced by companies (Barnett et al., 2020). Climate risks are divided into physical risks and transition risks (Financial Stability Board, FSB; Task Force on

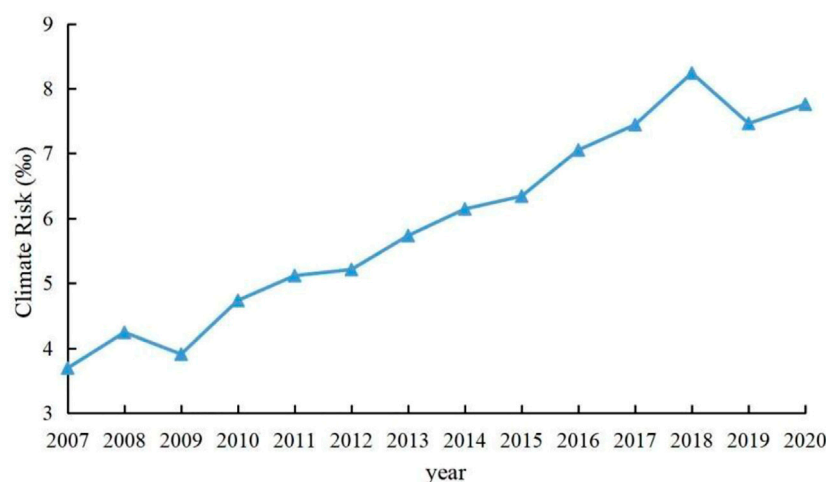


FIGURE 1

The trend of climate risk changes from 2007 to 2020.

TABLE 1 Describes statistics.

Variables	Obs	Mean	P25	P50	P75	Std. Dev	Min	Max
<i>PreCash</i>	25,889	0.0120	-0.0325	0.0023	0.0418	0.0977	-0.2150	0.6794
<i>ClimRisk</i>	25,889	0.0064	0.0008	0.0026	0.0075	0.0100	0.0000	0.0579
<i>Size</i>	25,889	22.0517	21.1226	21.8782	22.7800	1.2543	19.8134	25.8108
<i>Lev</i>	25,889	0.4354	0.2720	0.4312	0.5905	0.2038	0.0563	0.8754
<i>Age</i>	25,889	2.7700	2.5649	2.8332	3.0445	0.3702	1.6094	3.4340
<i>TobinQ</i>	25,889	1.9372	1.2308	1.5761	2.2126	1.1157	0.9022	7.4037
<i>Mshare</i>	25,889	0.4759	0.3145	0.4945	0.6482	0.2296	0.0021	0.9999

Climate-related Financial Disclosure, TCFD). Physical risks refer to asset loss caused by extreme weather (such as drought, flood and hurricane) and long-term climate change (such as climate warming and sea level rise). In the short term, more frequent and severe extreme weather brings the risk of production facilities damage and value chain interruption to the companies; In the long term, global and regional long-term climate change lead to the reduction of output in agriculture, labor and material (Ebi et al., 2021; Meyer et al., 2022). Transition risks refer to the risks arising during the society transiting to a low-carbon and climate adaptive economy, including all risks caused by policies, laws, technologies, market sentiment, reputation, etc. For example, more or stricter policies transformation increases the operating costs of companies (Dunz et al., 2019; Zhang and Cheng, 2022). Facing the uncertainty caused by climate risk, companies usually take preventive measures (Desing and Widmer, 2021), such as adjusting companies' precautionary cash holding strategies.

The attitude and ability of companies to deal with climate risks are crucial to mitigate uncertainty risks (Todaro et al., 2021). Risk taking reflects corporate managers' risk preference and risk control (Li and Tang, 2010; Wen et al., 2021). Higher risk taking can stimulate corporate potential and help companies gain

advantages in long-term competition, while lower risk taking can maintain stable growth of corporate performance. In the case of high climate risk, corporate managers are more likely to adopt conservative investment strategies to avoid investment risks. That is, companies facing high climate risk have low risk taking. Zhou D. et al. (2022a) found that the temperature rising significantly hinder corporate risk investment, thus reducing corporate risk-taking level. And the management's trade-off between risk and return determines the cash holdings scale of a company. (Chen et al., 2012; Gao et al., 2013; Harford et al., 2014). As the value of cash is not easily affected by market price fluctuations and cash turnover is fast, cash holding has lower risk than other forms of assets (Lei et al., 2022). Based on this, cash, as a type of asset with high liquidity and low risk, is favored by risk averter. Although holding cash does not typically generate large profits for companies, it is unlikely to result in significant investment losses (Zhou M. et al., 2022b). Companies with cautious management and low risk taking would hold more cash for long-term stable development (Bates et al., 2009; Xu et al., 2016). Therefore, when faced with high climate risk, companies will reduce risk taking and thus increase precautionary cash holdings.

TABLE 2 Baseline regression results.

Variables	PreCash	PreCash	PreCash	PreCash
	(1)	(2)	(3)	(4)
<i>ClimRisk</i>	0.1933*** (0.0616)	0.3484*** (0.0982)	0.3281*** (0.0994)	0.3463*** (0.0985)
<i>Size</i>	−0.0027*** (0.0007)	−0.0201*** (0.0020)	−0.0236*** (0.0021)	−0.0207*** (0.0021)
<i>Lev</i>	0.0662*** (0.0042)	0.0961*** (0.0077)	0.1125*** (0.0076)	0.0982*** (0.0076)
<i>Age</i>	0.0147*** (0.0017)	0.0831*** (0.0091)	0.0599*** (0.0043)	0.0842*** (0.0091)
<i>TobinQ</i>	0.0091*** (0.0009)	0.0108*** (0.0013)	0.0090*** (0.0011)	0.0109*** (0.0013)
<i>Mshare</i>	0.0030 (0.0031)	0.0139*** (0.0044)	−0.0016 (0.0041)	0.0138*** (0.0044)
<i>Constant</i>	−0.0184 (0.0146)	0.2016*** (0.0444)	0.3080*** (0.0373)	0.2146*** (0.0458)
<i>Year_FE</i>	No	Yes	No	Yes
<i>Industry_FE</i>	No	No	Yes	Yes
<i>Observations</i>	25,889	25,889	25,889	25,889
<i>R²</i>	0.0243	0.0505	0.0318	0.0511

Note: (1) *, **, *** represent significance at the 10%, 5%, and 1% significance level, respectively; (2) standard deviations are provided in parentheses.

In addition, a company with higher climate risk is faced with the dilemma of costs rising, revenues falling and profits declining, which increases the possibility that the company cannot afford debts so that it threatens the stability and development of financial institutions (Cai et al., 2019). Considering own interests and social responsibilities, banks would control the loans scale to companies with high climate risk, which result in a decline in these companies' external financing (Huang et al., 2022). For example, more than 30 major banks around the world indicate that they will no longer provide financing services for coal related projects or coal power companies. These companies with unfavorable financing constraints can only use their own funds for R&D activities. The decline in external financing causes companies to face the risk of bankruptcy liquidation due to capital chain rupture, thus companies need to make positive dynamic adjustments of cash holdings to deal with this risk (Denis and Sibilkov, 2010). Companies easy to obtain external financing are more likely to choose external financing rather than internal cash as a tool for market competition and access to investment opportunities. On the contrary, for companies that are not easy to obtain external financing, their cash holdings are more likely to play a competitive effect in the market (Beck and Demircuc-Kunt, 2006). Thus, in order to maintain liquidity and meet the needs of future investment, companies with external financing shortage would limit the current budget and increase cash holdings (Almeida et al., 2004). And when faced with high climate risk, corporate external financing decreases, and thus companies increase their precautionary cash holdings.

To sum up, companies would take preventive measures when facing uncertainty caused by climate risk, and adjusting precautionary cash holdings is the best measure to deal with the uncertainty. On the one hand, companies with higher climate risks would be more cautious, thus reducing risk taking. On the other hand, it is more difficult for companies to obtain bank loans when the climate risk increases, which means external financing of companies decreases. And precautionary cash can alleviate the shortage of investment and financing when companies face uncertain risks. Therefore, climate risk increases the uncertainty faced by companies, while increasing precautionary cash holdings can reduce this adverse effect. Therefore, we propose:

Hypothesis 1. Climate risk has a positive impact on precautionary cash holdings.

3 Research design

3.1 Variables

3.1.1 Climate risk

Based on the text analysis of MD&A disclosure, this study constructs a climate risk perception index to measure the climate risk faced by companies. Following to existing research (Choi et al., 2020; Tian et al., 2022a), we construct the climate risk index in three

TABLE 3 The regression results of region heterogeneity.

Variables	PreCash		
	Eastern	Central	Western
	(1)	(2)	(3)
<i>ClimRisk</i>	0.3328**	0.4270**	0.3136
	(0.1333)	(0.1768)	(0.2072)
<i>Size</i>	−0.0232***	−0.0165***	−0.0221***
	(0.0026)	(0.0045)	(0.0053)
<i>Lev</i>	0.1078***	0.0965***	0.0733***
	(0.0096)	(0.0154)	(0.0191)
<i>Age</i>	0.0849***	0.0827***	0.0815***
	(0.0103)	(0.0253)	(0.0305)
<i>TobinQ</i>	0.0109***	0.0094***	0.0137***
	(0.0016)	(0.0027)	(0.0039)
<i>Mshare</i>	0.0115**	0.0205*	0.0145
	(0.0053)	(0.0105)	(0.0114)
<i>Constant</i>	0.2818***	0.1165	0.2232*
	(0.0559)	(0.1094)	(0.1239)
<i>Year_FE</i>	Yes	Yes	Yes
<i>Industry_FE</i>	Yes	Yes	Yes
<i>Observations</i>	17,756	4,408	3,725
<i>R</i> ²	0.0580	0.0521	0.0477

Note: (1) *, **, *** represent significance at the 10%, 5%, and 1% significance level, respectively; (2) standard deviations are provided in parentheses.

steps: First, we select the seed word set of climate risk in MD&A including the causes (such as global warming, air pollution), reflections (such as storms, soil erosion) and results (such as environmental governance, energy saving and emission reduction) of climate risk. Secondly, using the deep learning technology provided by the Wingo financial text data platform¹, we select an expanded word set which has a similarity of 0.5 or more with the seed word set, and remove duplicate words. To remain objectivity, we invite three experts in academics and industry to triangulate the expanded word set, and finally determine the climate risk seed word set containing 271 seed words. Finally, we make word frequency statistics on the climate risk seed word set in each MD&A document and calculate the ratio of climate risk seed word's frequency to MD&A's total word frequency, then the climate risk perception index of the company is obtained. The larger the climate risk perception value of a company is, the higher climate risk the company faces.

3.1.2 Precautionary cash holdings

Following Almeida et al. (2004), Sun and Wang (2015) and Su et al. (2020), the precautionary cash holdings ($PreCash_{it}$) are measured by the ratio of the added value of cash and cash

equivalents to the total assets minus the ending balance of cash and cash equivalents:

$$PreCash_{it} = \frac{\Delta Cash \text{ and Cash Equivalents}_{it}}{Total Assets_{it} - Cash \text{ and Cash Equivalents}_{it}} \quad (1)$$

3.1.3 Mediation variables

3.1.3.1 Risk taking

We quantify risk taking from the perspective of earnings volatility (VOL). Following John et al. (2008), corporate profitability is measured by the return on assets. Considering that the term of office of senior managers of listed companies in China is generally three years, we use the standard deviation of return on assets of a company within three years to measure its earnings volatility. The larger a company's standard deviation of the return on assets is, the greater its earnings volatility is, and the higher risk taking the company faces.

3.1.3.2 External financing

Stock and bond markets are immature in China, and bank loans is the main source of external financing for companies. Thus, most Chinese companies rely on banks, and most of their loans are supported by bank loans (Firth et al., 2012; Liu et al., 2018). Following Su et al., (2020), we measure external financing (BLR) with the ratio of short-term loans plus long-term loans due

¹ <http://www.wingodata.com>.

TABLE 4 The regression results of scale heterogeneity.

Variables	PreCash	
	Large	Small
	(1)	(2)
<i>ClimRisk</i>	0.0025	0.7140***
	(0.0980)	(0.2189)
<i>Size</i>	−0.0370***	−0.0182***
	(0.0036)	(0.0050)
<i>Lev</i>	0.0685***	0.1430***
	(0.0103)	(0.0132)
<i>Age</i>	0.0288**	0.1010***
	(0.0130)	(0.0186)
<i>TobinQ</i>	0.0109***	0.0103***
	(0.0022)	(0.0019)
<i>Mshare</i>	0.0085	0.0143*
	(0.0056)	(0.0075)
<i>Constant</i>	0.7102***	0.1115
	(0.0834)	(0.1015)
<i>Year_FE</i>	Yes	Yes
<i>Industry_FE</i>	Yes	Yes
<i>Observations</i>	12,913	12,976
<i>R</i> ²	0.0480	0.0630

Note: (1) *, **, *** represent significance at the 10%, 5%, and 1% significance level, respectively; (2) standard deviations are provided in parentheses.

in one year to total assets. The larger this value is, the larger the company's external financing scale is.

3.1.4 Control variables

Based on existing researches about precautionary cash holdings (Su et al., 2020; Xiong et al., 2021; Zhang and Cheng, 2022), we select total assets (*Size*), debt-to-asset ratio (*Lev*), company age (*Age*), Tobin's Q (*TobinQ*), managements shareholdings ratio (*Mshare*) as the control variables. The definitions of variables used in this study are provided in Appendix.

3.2 Data and descriptive statistics

3.2.1 Data sources

Since 2007, China's accounting standards have acted on international convention, and new "The Corporate Accounting Standards" has been implemented. To avoid the impact of differences in accounting standards before and after, we construct sample based on Chinese listed companies from 2007 to 2020. And we remove observations from initial samples as follows: 1) financial service and insurance industry, 2) firms with less than 2 years' available data, and 3) special treatment (ST) and *ST companies. The information of corporate management discussion and analysis (MD&A) is collected from Cninfo website, and other data are acquired from the *China Stock Market and Accounting Research* (CSMAR) database. To avoid the influence of outliers, all continuous variables are

winsorized at the upper and lower 1% levels. Finally, we obtain 25,889 firm-year observations from 3,377 Chinese listed companies.

3.2.2 Descriptive statistics

3.2.2.1 Description of climate risk change trend

Figure 1 shows the change trend of average climate risk faced by companies from 2007 to 2020. The overall trend of climate risk faced by companies is on the rise, that is, companies' climate risk is increasingly high. In addition, the climate risk index constructed in this study is significantly related to China's climate risk score in the global Climate Risk Index (CRI) prepared by Germany at the 1% level, which indicates the reliability of our climate risk index.²

3.2.2.2 Descriptive statistics

Table 1 provides a brief summary of descriptive statistics for main variables. Precautionary cash holdings (*PreCash*) have a mean of 0.0120, a standard deviation of 0.0977, a minimum of −0.2150 and a maximum of 0.6794. And climate risk (*ClimRisk*) has a mean of 0.0064, a standard deviation of 0.0100, a minimum of 0 and a maximum of 0.0579. It indicates that the key indicators fluctuate greatly within our study setting.

² Details of this result can be obtained from the author.

TABLE 5 The mediating effect of risk taking and external financing.

Variables	VOL	PreCash	BLR	PreCash
	(1)	(2)	(3)	(4)
<i>ClimRisk</i>	−0.1697*** (0.0428)	0.3258*** (0.0983)	−0.3612*** (0.1040)	0.3322*** (0.1013)
<i>VOL</i>		−0.1531*** (0.0209)		
<i>BLR</i>				−0.0268** (0.0108)
<i>Size</i>	−0.0086*** (0.0011)	−0.0220*** (0.0021)	−0.0033 (0.0023)	−0.0205*** (0.0021)
<i>Lev</i>	0.0320*** (0.0046)	0.1038*** (0.0077)	0.2659*** (0.0085)	0.1056*** (0.0091)
<i>Age</i>	0.0036 (0.0058)	0.0845*** (0.0092)	0.0163 (0.0118)	0.0831*** (0.0094)
<i>TobinQ</i>	0.0017*** (0.0005)	0.0111*** (0.0013)	−0.0041*** (0.0010)	0.0108*** (0.0014)
<i>Mshare</i>	−0.0169*** (0.0020)	0.0114*** (0.0044)	−0.0057 (0.0040)	0.0127*** (0.0044)
<i>Constant</i>	0.1749*** (0.0285)	0.2414*** (0.0460)	0.0645 (0.0586)	0.2165*** (0.0474)
<i>Year_FE</i>	Yes	Yes	Yes	Yes
<i>Industry_FE</i>	Yes	Yes	Yes	Yes
<i>Observations</i>	25,851	25,851	24,038	24,038
<i>R²</i>	0.0566	0.0539	0.1941	0.0531

Note: (1) *, **, *** represent significance at the 10%, 5%, and 1% significance level, respectively; (2) standard deviations are provided in parentheses.

3.3 Model

3.3.1 Baseline model

This study examines the relationship between climate risk and precautionary cash holdings by the following panel regression model:

$$PreCash_{it} = \alpha + \alpha_1 ClimRisk_{it} + \sum_k \beta_k Z_{it} + Year\ FE + IndustryFE + \varepsilon_{it} \quad (2)$$

where $PreCash_{it}$ represents the precautionary cash holdings of company i in year t ; $ClimRisk_{it}$ represents the climate risk faced by company i in year t . Z_{it} represents control variables, which includes total assets (*Size*), debt-to-asset ratio (*Lev*), company age (*Age*), Tobin's Q (*TobinQ*), managements shareholdings ratio (*Mshare*). Year and industry fixed effects are controlled. And ε_{it} is the random error term.

3.3.2 Mediator model

Following Edwards and Lambert (2007), we examine the mediating effect of risk taking and external financing by the following models:

$$M_{it} = \mu_0 + \mu_1 ClimRisk_{it} + \sum_k \omega_k Z_{it} + Year\ FE + IndustryFE + \varepsilon_{it} \quad (3)$$

$$PreCash_{it} = \varphi_0 + \varphi_1 ClimRisk_{it} + \varphi_2 M_{it} + \sum_k \gamma_k Z_{it} + Year\ FE + IndustryFE + \varepsilon_{it} \quad (4)$$

where M_{it} represents intermediate variable, which includes risk taking (*VOL*) and external financing (*BLR*). The definitions of other variables are identical to those of the Eq. 2.

4 Results

4.1 Baseline regression results

Table 2 shows the baseline regression results. Column (1) is the mixture regression result. Column (2) and column (3) show the results of regression with year fixed effect and that with industry fixed effect respectively. And column (4) shows the regression results with both year fixed effect and industry fixed effect. These results all show that the coefficient of *ClimRisk* is positive and significant at the 1% level, which is consistent with Hypothesis 1, meaning that a company would increase its precautionary cash holdings when the climate risk increases.

TABLE 6 Robustness tests.

Variables	PreCash1	PreCash	PreCash	PreCash	PreCash	PreCash
	(1)	(2)	(3)	(4)	(5)	(6)
<i>ClimRisk</i>	0.2954*** (0.0863)	0.5291*** (0.1657)	0.3159*** (0.1075)	0.3058*** (0.1019)	0.3099*** (0.1023)	0.3099*** (0.0979)
<i>Size</i>	−0.0236*** (0.0019)	−0.0206*** (0.0021)	−0.0223*** (0.0022)	−0.0209*** (0.0021)	−0.0212*** (0.0022)	−0.0190*** (0.0021)
<i>Lev</i>	0.1111*** (0.0068)	0.0980*** (0.0076)	0.1053*** (0.0083)	0.1051*** (0.0079)	0.1032*** (0.0078)	0.1032*** (0.0076)
<i>Age</i>	0.0906*** (0.0086)	0.0842*** (0.0091)	0.0847*** (0.0098)	0.0812*** (0.0093)	0.0825*** (0.0093)	0.0743*** (0.0088)
<i>TobinQ</i>	0.0132*** (0.0012)	0.0109*** (0.0013)	0.0111*** (0.0014)	0.0114*** (0.0014)	0.0115*** (0.0013)	0.0114*** (0.0013)
<i>Mshare</i>	0.0062 (0.0039)	0.0138*** (0.0044)	0.0141*** (0.0046)	0.0148*** (0.0045)	0.0136*** (0.0045)	0.0297*** (0.0036)
<i>CGE</i>			0.0063 (0.0041)			
<i>GDP</i>				−0.0005 (0.0006)		
<i>Constant</i>	0.2505*** (0.0420)	0.2133*** (0.0457)	0.1524** (0.0737)	0.2281*** (0.0470)	0.2417*** (0.0511)	0.1943*** (0.0476)
<i>Year_FE</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Industry_FE</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>City_FE</i>	No	No	No	No	No	Yes
<i>Observations</i>	25,889	25,889	22,935	24,287	24,551	25,781
<i>R²</i>	0.0737	0.0510	0.0533	0.0535	0.0589	0.0612

Note: (1) *, **, *** represent significance at the 10%, 5%, and 1% significance level, respectively; (2) standard deviations are provided in parentheses.

4.2 Heterogeneity analysis

4.2.1 Region heterogeneity

The climate risk faced by a company depends on the region where the company is located (Ginglinger and Moreau, 2019). Compared with the western region, the eastern and central regions of China face higher cost of environmental governance and more serious climate impacts. And the eastern and central regions of China have a higher degree of marketization and a better market system (Ren et al., 2022). Companies located in the eastern and central regions are more sensitive to climate change when they change their business and investment, and these companies enable adapt to the changing climate risks with various strategies. Thus, in order to catch the moderating effect of climate risk and precautionary cash holdings in the region where the company is located, we test the region heterogeneity of the impact of climate risk on precautionary cash holdings. Specifically, we conduct sub sample regression on the companies located in the eastern, central and western regions of China.

The regression results are shown in Table 3. Column (1) to column (3) respectively report the regression results of the climate risk of

companies in eastern, central and western China on their precautionary cash holdings. Climate risk has a significant and positive impact on precautionary cash holdings for companies located in eastern and central China, while it is not significant for companies in western China.

4.2.2 Scale heterogeneity

Corporate size is another important company-level consideration that affects precautionary cash holdings (Nguyen et al., 2016). Corporate scale reflects the overall capability and performance of the company. Due to China's special institutional background, large-scale companies hold most bank credit, while limited credit funds from state-owned financial institutions is available for small-scale companies. Compared with large-scale companies, small-scale companies obtain external funds with stricter financing conditions and higher financing costs (Rostamkalaei and Freel, 2016). The uncertainty brought by climate risk further increases the difficulty for small-scale companies to achieve their financing goals. In order to effectively mitigate the possible adverse effects of climate risks

TABLE 7 Instrumental variable analysis.

Variables	ClimRisk	PreCash
	1st stage	2nd stage
	(1)	(2)
<i>Mean ClimRisk</i>	0.9155***	
	(0.0768)	
<i>ClimRisk</i>		1.3407**
		(0.6432)
<i>Size</i>	0.0006***	−0.0002
	(0.0001)	(0.0007)
<i>Lev</i>	0.0023***	0.0461***
	(0.0003)	(0.0042)
<i>Age</i>	−0.0008***	0.0103***
	(0.0002)	(0.0021)
<i>TobinQ</i>	−0.0006***	0.0101***
	(0.0001)	(0.0010)
<i>Mshare</i>	0.0006***	0.0111***
	(0.0003)	(0.0032)
<i>Constant</i>	−0.0117***	−0.0337**
	(0.0014)	(0.0159)
<i>Year_FE</i>	Yes	Yes
<i>Industry_FE</i>	Yes	Yes
<i>Observations</i>	25,880	25,880
<i>R²</i>	0.1192	0.0251

Note: (1) *, **, *** represent significance at the 10%, 5%, and 1% significance level, respectively; (2) Standard deviations are provided in parentheses.

and take potential market opportunities, small-scale companies would make decisions quickly to change conventional practices (Crick et al., 2018). Thus, we analyze scale heterogeneity to identify the moderating effect of corporate scale on climate risk and precautionary cash holdings. If the total assets of a company are above the median of the total assets of all companies, we regard this company as a large-scale company; otherwise, a small-scale company.

The regression results are shown in Table 4. Column (1) and column (2) in Table 4 respectively show the regression results of climate risk of large-scale companies and small-scale companies on precautionary cash holdings, suggesting climate risk has a significant and positive impact on precautionary cash holdings in small-scale companies. However, no significant impact is observed in large-scale companies.

4.3 Channel analysis

In this section, we examine the mediating effect of risk taking (VOL) and external financing (BLR) in the impact of climate risk

on precautionary cash holdings. First, we examine whether the increase of companies' climate risk leads to the reduction of their risk taking level and external financing. Second, we examine the impact of risk taking and external financing on precautionary cash holdings. Table 5 shows the results of the above analysis.

Columns (1) and (3) in Table 5 report the results about the impact of climate risk on risk taking and external financing respectively, suggesting that climate risk has a negative and significant impact on risk taking and external financing. It indicates that companies' risk taking and external financing decrease with the increase of climate risk. Columns (2) and (4) respectively report the results about the impacts of risk taking and external financing on precautionary cash holdings, suggesting that risk taking and external financing both have a significantly negative impact on precautionary cash holdings. It indicates that the lower the risk taking is or the less the external financing is, the higher precautionary cash holdings a company has. Therefore, the climate risk faced by companies affects precautionary cash holdings through risk taking and external financing, that is, risk taking and external financing make a mediating effect between climate risk and precautionary cash holdings.

5 Robustness tests

In this section, we conduct a battery of robustness checks. First, we re-estimate the baseline regression with another measure of precautionary cash holdings. Following the existing literature (Lin et al., 2021; Hasan et al., 2022; Seo and Han, 2022), we use the ratio of the increase in cash and cash equivalents to the total assets to measure the company's precautionary cash holdings. The results are shown in column (1) of Table 6, which support our key findings that the impact of climate risk on precautionary cash holdings is significantly positive. Second, following Tian et al. (2022b), we select an expanded word set which has a similarity of 0.6 or more with the seed word set to construct climate risk indicators and then re-estimate the baseline regression. The results are shown in column (2) of Table 6, suggesting that the coefficient of *ClimRisk* is still positive and significant. Third, we consider eliminating the possible impact of macroeconomic factors on our research. Thus, we follow Su et al., (2020) to test the robustness of the baseline results by controlling local fiscal expenditure (CEG), *per capita* GDP (GDP) and urban fixed effects respectively. The results of these tests are given in columns (3) to (5), which shows that climate risk still has a significantly positive impact on precautionary cash holdings. Last, considering that sample period includes the global financial crisis period (GFC) (2008–2009), we follow Nguyen and Phan (2020) to exclude the GFC years from the sample period, which mitigates the impact of the financial crisis on the research results. Column (6) of Table 6 shows this result. And the coefficient of *ClimRisk* is still significantly positive at the level of 1%, suggesting our findings are robust and reliable³.

The baseline results of this study indicate that companies faced by high climate risk would increase precautionary cash holdings. And companies with high precautionary cash holdings are more likely to invest green projects, which affects their climate risk perception. Thus, the above studies may have endogenous problems. To solve these possible endogenous problems, we introduce instrumental variable. Inspired by Wintoki et al. (2012), we use the mean of all companies' climate risk in the same industry over the years (*Mean ClimRisk*) as an instrumental variable for two-stage regression. The results of the two-stage regression are shown in Table 7. In the first stage of regression, we use the mean of climate risk in the industry where the company is in over the years and all control variables to explain the long-term level of climate risk. Column (1) is the result of the first stage. The coefficient of *Mean ClimRisk* is positive and significant and the F value is 119.28 which is far greater than 10, suggesting that there is a significant positive correlation between the mean of climate risk in the industry where the company is in over the years and the climate risk faced by the company. In the second stage of regression, we analyze the regression relationship between the precautionary cash holdings and the fitting value of climate risk in the first stage, and control

variables are added. Column (2) of Table 7 shows the result that the coefficient of *ClimRisk* is still positive and significant. This test alleviates the endogenous problem to a certain extent. Moreover, the results of two-stage regression also support our baseline results, that is, climate risk has a significantly positive impact on precautionary cash holdings.

6 Conclusion

This study takes China's listed companies from 2007 to 2020 as the research setting and uses text mining technology to measure corporate climate risk perception which represents the level of climate risk faced by companies. We then use panel regression model and mediator model to respectively test the impact and impact channels of climate risk on corporate precautionary cash holdings. The results indicate that there is a significant and positive relationship between climate risk and corporate precautionary cash holdings. That is, the higher climate risk a company faces, the more precautionary cash holdings the company holds. We further explore the heterogeneous effects of region and scale. In terms of region heterogeneity, climate risk has a significantly positive impact on precautionary cash holdings of companies in eastern and central China, but no significant impact is observed in companies in Western China. In terms of scale heterogeneity, climate risk has a significantly positive impact on precautionary cash holdings of large-size companies, while has no significant impact on that of small-size companies. In addition, risk taking and external financing have mediating effects between climate risk and precautionary cash holdings. In other words, the climate risk faced by companies affects corporate precautionary cash holdings through affecting companies' risk taking and external financing.

Based on the research conclusions, we make the following three suggestions for companies to cope with climate risks. First, while sensing climate risks, the company should develop reasonable preventive strategies and adjust precautionary cash holdings in time to meet the need of sustainable development. Second, in the case of high climate risk, changing environmental policies will increase companies' investment risk. Companies need sharp risk awareness and control force to weight between risk and return. And companies should reasonably estimate its risk-taking level and select projects with low risk and stable income. Third, climate risk intensifies the information asymmetry in the capital market, which leads to the decrease of corporate external financing. On the one hand, banks should carefully identify corporate risk information and conduct credit risk assessment on specific projects, so as to avoid relying on industry attributes to make credit decisions which cause financial difficulties for company transformation. On the other hand, companies should enhance comprehensive strength to meet the investment requirements of financial institutions and investors.

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.

³ We also tested the robustness not only with using the explanatory variable lagged for one period, but also using one-period lagged explanatory variable and one-period lagged control variables. The results did not change and can be obtained from the author.

Author contributions

WZ: Methodology, validation, supervision. KY: Methodology, formal analysis, software, writing—review and editing. YL: Data curation, writing—original draft preparation. KY: Software, formal analysis, writing—original draft preparation. YL: Software, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

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Appendix

TABLE A1 Variable definitions.

Variables	Definitions
<i>CASH</i>	The ratio of the added value of cash and cash equivalents to the total assets minus the ending balance of cash and cash equivalents
<i>ClimRisk</i>	The ratio of the word frequency about climate risk perception in management discussion and analysis (MD&A) to the total word frequency of MD&A
<i>SIZE</i>	Logarithm of total assets
<i>LEV</i>	Book value of total liabilities divided by book value of total assets
<i>TobinQ</i>	Net profit divided by the average balance of shareholders' equity
<i>AGE</i>	Logarithm of listing age
<i>Mshare</i>	The ratio of shares held by managements in total shares



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Environmental information disclosure and stock price crash risk: Evidence from China

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Environmental performances have gained great prominence for firms in recent years. This paper empirically tests the relationship between environmental information disclosure and the risk of stock price crashes based on a sample of Chinese A-share listed firms from 2013–2018. The results show that environmental information disclosure has a significant negative correlation with stock price crash risk, with mechanism analysis showing that media coverage plays an intermediary role between them. Further analysis finds that: first, the inhibitory effect of environmental information disclosure on stock price crashes is more significant in companies with a lower proportion of independent directors, which reflects the supervision effect of environmental information disclosure. Second, the role of environmental information disclosure has a greater negative impact on the risk of stock price crashes in industries with low competition, indicating that environmental information disclosure is not a tool for enterprises to compete for resources. Third, the profit motivation of institutional investors restrains the negative impact of environmental information disclosure on price collapse risk. Forth, the level of government environmental governance is an important support for enterprise environmental information disclosure.

KEYWORDS

environmental information disclosure, nonfinancial information disclosure, media coverage, stock price crash risk, corporate governance

1 Introduction

As the Chinese economy has entered a stage of high-quality development, it is crucial to continuously improve the capital market that serves the development of the real economy. However, along with high growth, China's stock market also has the problem of vulnerability, especially the frequent crashes and collapses of the stock market after the 2008 financial crisis, which poses a challenge to China's economic security and sustainable development. Regarding the causes of stock price crashes, based on principal-agent theory and information asymmetry theory, the relevant literature generally finds that company executives choose to hide the company's "bad news" out of self-interested motives such as maintaining a reputation (Jin and Myers, 2006). As adverse news continues to accumulate until it is impossible to hide, it will suddenly explode in the capital market, leading to the rapid decline of individual stock prices and forming a so-called stock price crash. In this process, the lack of information disclosure leads to the decline of information transparency, regarded as an important factor in stock price crashes.

Information disclosure is not only a strong guarantee of improving the level of corporate governance but also the institutional cornerstone of the healthy development of capital markets. Information disclosure can be divided into financial information disclosure and non-financial information disclosure, although previous studies have focused more on financial information.

For example, [Hutton et al. \(2009\)](#) showed that the lack of transparency in financial reports increased the risk of a company's stock price crash; and [Zhu et al., 2020](#)) argued that internet information interaction could improve the authenticity of corporate financial information, encourage investors to form reasonable expectations, and avoid the occurrence of stock price crashes. With the deepening of research, some scholars have turned to non-financial information disclosure, such as the impact of corporate social responsibility on stock price crashes ([Kim et al., 2014](#)), but the coverage of relevant non-financial information research is narrow, and the content in developing countries is deficient ([Tao et al., 2022](#)). As an important aspect of information disclosure, a consensus has been formed on the role of non-financial information disclosure in improving the information environment of capital markets ([Hu and Tan, 2013](#)). Therefore, it is necessary to combine different corporate internal governance and external environments to discuss from the perspective of non-financial information disclosure, which will help provide a comprehensive, in-depth understanding of the causes of stock price crash risk. From the perspective of environmental information disclosure, this paper attempts to answer the following questions: What is the relationship between environmental information disclosure and stock price crash risk? How can media coverage play a role in this relationship? Does firm heterogeneity significantly affect the relationship?

Accordingly, this paper uses unbalanced panel data of 2,446 listed firms from 2013–2018 to empirically test the relationship between environmental information disclosure and stock price crash risk. The main reasons for choosing the Chinese market are as follows. First, China has grown into the world's second largest economy in recent years, but its capital market is still immature. There have been repeated stock price crashes in recent years, such as the financial crisis in 2008 and the 1,000-share crash in 2015. It means that the market is vulnerable to the impact of information shocks, and the stock price will have frequent ups and downs, with poor stability and self-correction ability. Second, as the world's largest emerging capital market, its participants are mainly retail investors, and compared with developed markets, the information disclosure system is not perfect. China's unique macro environment provides a good foundation for studying the impact of information disclosure. Therefore, Under the current economic downward pressure and the capital market is unstable, exploring the risk management mechanism of stock price crash in the Chinese market is helpful to maintain the stability of the capital market. At the same time, it can also provide reference for other emerging economies and developing countries with excess resource consumption to resolve enterprise risks through market-oriented means. Third, The accelerating climate change concerns highlight the importance of reducing fossil fuel consumption ([Tian et al., 2022](#)). China's sustained high economic growth has accompanied the sharp increase in resources and energy consumption ([Kang et al., 2022](#)), environmental information disclosure can be regarded as an important symbol for enterprises to reduce energy consumption, therefore research on environmental information disclosure can contribute to energy transition.

The results show that environmental information disclosure is significantly negatively correlated with the risk of stock price crashes, which is still significant after using the instrumental variable method, propensity score matching (PSM) method, replacement variables and

other robustness tests. The mechanism analysis shows that media coverage plays a mediating role in the inhibitory effect of environmental information disclosure on stock price crash risk. Further analysis shows that the characteristics of the board of directors, the pressure of industry competition, the shareholding ratio of institutional investors and the level of government environmental governance are important factors affecting the relationship.

The contributions of this paper are as follows. First, it expands the research on the influencing factors of stock price crash risk. Based on the perspective of financial information disclosure projects and supervision, existing studies have confirmed that the improvement of financial information quality significantly reduces the risk of stock price crashes, but the discussion on the influence of non-financial information disclosure on stock prices is still insufficient in developing countries ([Tao et al., 2022](#)). An analysis based on environmental information disclosure will undoubtedly enrich the research in related fields. Second, based on different market participants, this paper conducts an in-depth examination of the impact of environmental information disclosure on stock price crash risk. Most of the literature continues the research approach of [Chen et al. \(2001\)](#) to analyze the mechanism of stock price crash risk from the perspective of corporate governance ([Song et al., 2017](#)). In this paper, however, the possible market reaction to the company's non-financial information is included in the research category of stock price crash risk mechanism analysis. It is useful to deepen and extend the understanding and analytical paradigm of the causes of stock price crash risk, which has profound theoretical and practical significance. Third, considering the macro background of China's green development and ecological civilization construction, our paper attempts to explore the impact of corporate environmental information disclosure on the capital market to provide empirical evidence on the economic consequences of implementing the green development concept and actively fulfilling environmental responsibility for enterprises. In addition, the heterogeneity analysis results also provide support for the development of environmental information disclosure policies of relevant departments and the decision-making of enterprise environmental information disclosure.

2 Hypothesis

Stock price crashes are an important topic in the field of asset pricing and corporate finance. Existing studies focus on the formation mechanism of stock price crashes and discuss the principal-agent problem and the corporate information environment. According to agency theory, the root cause of stock price crashes is that the company's senior executives, motivated by self-interest, including the pursuit of higher salary, honor and status, use their authority to exercise opportunistic behavior and deliberately conceal the company's adverse news, which eventually leads to the crash of the stock price ([Jin and Myers, 2006](#)). [Kim et al. \(2014\)](#) found that to maximize the value of short-term stock options, CEOs and CFOs are motivated to hide adverse news, leading to an increased risk of a stock price crash. Scholars have provided explanations from the perspective of

corporate governance, including the number of shareholders, the proportion of major shareholders, the reduction of senior executives' holdings, and the equity pledge of controlling shareholders. In terms of the information environment, Jin and Myers (2006) empirically tested the impact of information transparency differences between countries on stock prices using data at the national level and found that countries with lower information transparency had higher stock price crash risk. Hutton et al. (2009) turned the research subject to companies and found that corporate financial transparency significantly affected the probability of stock price crashes. The higher the transparency, the lower the probability of stock price crash risk. On this basis, Kim et al. (2014) conducted a more in-depth study. Based on the perspective of implied volatility, they found that the restatement of financial reports, earnings management and internal control defects would increase the occurrence of stock price crash risks. Other scholars have conducted research from the perspective of external supervision, including tax regulation (Kim et al., 2011; Chen et al., 2022), media reports (An et al., 2020; Hossain et al., 2022), institutional investors (Xiang et al., 2020), and investor sentiment (Fu et al., 2021).

The research on corporate environmental information disclosure mainly focuses on the following aspects: First, the content, mode and current situation of environmental information disclosure. Most scholars believe that the contents of environmental information disclosure should include environmental problems, impacts and corresponding countermeasures, as well as environment-related costs and benefits and environmental liabilities (Cho and Patten, 2007), and studied the *status quo* of environmental information disclosure of heavy polluting enterprises in China (Luo et al., 2019). Second, research on the influencing factors of environmental information disclosure. Most scholars have discussed the influencing factors of corporate environmental information disclosure from internal factors and external factors. Among them, external factors mainly include government policies and regulations, environmental control intensity, accounting responsibility and public opinion pressure, etc. (Liu and Anbumozhi, 2009; Wang et al., 2013; Fang and Guo, 2018), internal factors are mainly enterprise size, industry type, green commitment and corporate governance (Yan and Chen, 2017; Jacoby et al., 2019; Liu et al., 2022a). Third, the impact of environmental information disclosure. Some scholars believe that environmental information disclosure can have a positive impact on corporate value through reducing information asymmetry, improving corporate investment efficiency (Liu et al., 2022b), enhancing corporate governance (Earnhart and Lizal, 2006) and influencing financial markets (Wan et al., 2021).

According to the theory of externalities, enterprises show positive or negative externalities in the pursuit of profit maximization (Tirole, 2001), but the management of the company is often unsatisfactory in dealing with negative externalities. Therefore, undertaking social responsibility can be regarded as an effort by enterprises to reduce their negative externalities (Magill et al., 2015) and has gradually become an effective way for enterprises to balance their own interests with those of other stakeholders (Ferrell et al., 2016). As a reflection of the interaction between enterprises and other stakeholders, environmental information disclosure is an important indicator to measure the attitude and strength of enterprises toward social responsibility. In general, it can not only reflect the internal information of the enterprise to investors but also affect the

external impression and reputation of the enterprise (Song et al., 2017), which has an important impact on the stock price of the enterprise. Specifically, environmental information disclosure can reduce the risk of stock price crashes in two ways: the information transfer effect and the reputation guarantee effect.

- (1) Information transfer effect. Generally, when the degree of information asymmetry between internal and external companies is high, firm executives are more likely to hide adverse news out of self-interest, which is the root of stock price crashes (Habib et al., 2018). On the one hand, according to signaling theory, enterprises can transmit internal information to the outside world through environmental information disclosure behavior, alleviate the information disadvantage of outsiders to a certain extent, inhibit the occurrence of concealment behavior by increasing the cost of hiding "bad news" by company executives, and reduce the probability of stock price collapse from the root. On the other hand, since environmental information disclosure transmits the relevant information about the enterprise, investors know the financial health status of the enterprise (Lizzeri, 1999); based on this, reasonable investment decisions can be made so that the stock price fully reflects the real business situation of the enterprise, avoiding the formation of stock price bubbles due to asymmetric information and the occurrence of stock price crashes at a certain point.
- (2) Reputation guarantee effect. According to the theory of reputation management, the influence of people's perceptions of current news cannot be underestimated. Corporate reputation provides conditions for eliminating adverse situations with the help of the public's mindset. Therefore, with the enhancement of public awareness of environmental protection, environmental information disclosure has gradually become an important means for enterprises to perform environmental protection duties and create a better image. Godfrey et al. (2009) pointed out that although this corporate reputation capital reflecting social morality could not directly bring benefits to the change in corporate capital stock and related transactions, it could play a role similar to insurance when enterprises are faced with adverse events. In other words, corporate reputation capital formed by environmental information disclosure can affect the public's subjective judgment of negative corporate news (for example, that corporate executives are just "doing bad things with good intentions"), delay the time and impact of adverse corporate information entering stock prices, and be able to deal with current problems and reduce the degree of "sanctions" (massive stock selling) (Godfrey et al., 2009).

Hypothesis 1: There is a significant negative correlation between environmental information disclosure and stock price crash risk.

In the relationship between environmental information disclosure and stock price crash risk, both the *ex ante* information transmission effect and the *ex post* reputation guarantee effect include the process of information transmission from enterprises to capital markets (investors). In this process, the information intermediary plays a vital role. Existing studies show that the media (Fang and Peress, 2009) play important information intermediary functions in the capital market.

TABLE 1 Variable definitions.

Name	Variable	Definitions
Stock Price Crash Risk	$NCSKEW_{t+1}$	The negative skewness of weekly stock returns in year $t+1$
	$DUVOL_{t+1}$	The volatility ratio of weekly stock returns in year $t+1$
Environmental Information Disclosure	$CEID_t$	Whether the company discloses environmental goals in year t
Media coverage	$media_t$	Log (number of news articles on Baidu + 1)
market returns	ret_t	Average weekly holding return of stock i in year t
market volatility	$sigma_t$	Standard deviation of stock holdings in year t
Stock turnover	$turn_t$	Average weekly turnover rate of stock i in year t
Negative skewness coefficient of return	$NCSKEW_t$	The negative skewness of weekly stock returns in year t
Return on total assets	roa_t	Net profit/total assets
Growth rate of operating income	$growth_t$	(Current year operating income—last year operating income)/last year operating income
Debt asset ratio	lev_t	Total assets/total liabilities
Share ratio of the largest shareholder	$first_t$	The number of shares held by the largest shareholder/the total capital stock of the enterprise
Book to market ratio	mb_t	Market value/book value of equity
Firm size	$size_t$	The natural log of total enterprise assets
corporate transparency	$abacc_t$	Correct the absolute value of the residual of the Jones model
Audit quality	$big4_t$	Whether the company is audited by a Big Four accounting firm

TABLE 2 Descriptive statistics.

Variables	Obs	Mean	SD	Min	Max
$NCSKEW_{t+1}$	9,165	−0.226	0.660	−3.399	3.295
$DUVOL_{t+1}$	9,165	−0.0857	0.458	−1.839	2.038
$CEID_t$	9,165	0.100	0.301	0	1
$media_t$	9,165	1.624	1.881	0	6.788
ret_t	9,165	0.00194	0.0101	−0.0366	0.0488
$sigma_t$	9,165	0.0615	0.0210	0.0140	0.147
$turn_t$	9,165	−0.0788	0.399	−1.638	0.976
$NCSKEW_t$	9,165	−0.180	0.652	−3.477	3.295
roa_t	9,165	0.0363	0.0592	−0.293	0.196
$growth_t$	9,165	0.206	0.464	−0.561	2.966
lev_t	9,165	0.424	0.205	0.0521	1
$first_t$	9,165	33.72	14.66	3	90
mb_t	9,165	0.591	0.247	0.0176	1.430
$size_t$	9,165	22.20	1.231	19.07	25.78
$abacc_t$	9,165	0.0569	0.0568	0	0.268
$big4_t$	9,165	0.0439	0.205	0	1

Fang and Peress (2009) pointed out that the media have the function of information collection and dissemination, which improves the information available to investors. In the context of the extensive use of internet information technology in capital markets, media as information intermediaries play an increasingly critical role (Strycharz

et al., 2018). In the process of continuous emphasis on and improvement of ecological civilization construction, enterprise-related environmental protection information has gradually become a hot topic of media reports. Therefore, it can be predicted that corporate environmental information disclosure will cause an increase in media attention; that is, corporate environmental information disclosure may be positively correlated with media attention. Existing studies show that the media can reduce the risk of stock price crashes from many aspects, including alleviating the internal and external information asymmetry of the company, improving the efficiency of the capital market, reducing the time and space for executives to hide negative news, and improving public opinion supervision to alleviate the executive agency problem. In conclusion, environmental disclosure may reduce the risk of stock price crashes by increasing media coverage.

Hypothesis 2: In the relationship between environmental information disclosure and stock price crash risk, media coverage plays a mediating role.

3 Data and methodology

3.1 Data

This paper uses unbalanced panel data of 2,446 listed firms from 2013–2018. The shareholding data of institutional investors are obtained from the WIND database, media coverage is obtained from the Baidu News search index, and the remaining data are obtained from the CSMAR database. In November 2012, the 18th National Congress included ecological civilization construction in the “five-in-one” overall layout of the socialist cause with Chinese

TABLE 3 Basic regression results.

Variables	(1)	(2)	(3)	(4)
	$NCSKEW_{t+1}$	$DUVOL_{t+1}$	$NCSKEW_{t+1}$	$DUVOL_{t+1}$
$CEID_t$	−0.082***	−0.042***	−0.063***	−0.035**
	(0.023)	(0.016)	(0.023)	(0.016)
ret_t			12.155***	5.961***
			(1.032)	(0.722)
σ_{it}			0.859*	−1.176***
			(0.503)	(0.342)
$turn_t$			−0.036*	−0.007
			(0.019)	(0.013)
$NCSKEW_t$			0.066***	0.041***
			(0.011)	(0.007)
roa_t			0.127	0.254***
			(0.129)	(0.084)
$growth_t$			0.016	0.005
			(0.016)	(0.011)
lev_t			0.001	0.030
			(0.044)	(0.030)
$first_t$			−0.001*	−0.000
			(0.000)	(0.000)
mb_t			0.019	0.037
			(0.037)	(0.025)
$size_t$			−0.026***	−0.024***
			(0.008)	(0.005)
$abacc_t$			−0.115	−0.088
			(0.122)	(0.080)
$big4_t$			0.017	0.025
			(0.036)	(0.023)
Constant			0.181	0.465***
			(0.179)	(0.119)
Year	Yes	Yes	Yes	Yes
Ind	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
Observations	9,165	9,165	9,165	9,165
R ²	0.0699	0.1271	0.0937	0.1403

Note: *, **, and *** indicate significance at 10, 5 and 1% level, respectively. The first two columns do not consider control variables, and the last two columns introduce control variables.

characteristics. Since then, enterprises' participation in environmental protection has attracted wide attention. Drawing on his ideas, the samples selected in this paper started in 2013. As a rule, the research samples are processed as follows: 1) Abnormal

samples such as *ST* and *PT* are removed; 2) the financial industry is removed; 3) samples with missing variables are removed; and 4) to avoid the influence of outliers, winsorization is carried out on all continuous variables at the 1% and 99% levels.

3.2 Variable definitions

3.2.1 Dependent variable

Stock Price Crash Risk. The calculation process is as follows:

The following regression is performed on the weekly return rate of stock i by year:

$$R_{i,s} = \alpha_0 + \alpha_1 R_{m,s-2} + \alpha_2 R_{m,s-1} + \alpha_3 R_{m,s} + \alpha_4 R_{m,s+1} + \alpha_5 R_{m,s+2} + \varepsilon_{i,s} \quad (1)$$

where $R_{i,s}$ represents the return rate of stock i in week s , $R_{m,s}$ represents the market return rate weighted by the current market value in week s , and the unexplained part of $R_{i,s}$ is represented by the residual $\varepsilon_{i,s}$. To adjust the impact of non-synchronous trading, the two-period lead and two-period lag terms of market return are introduced in Eq. 1 $W_{i,s} = \ln(1 + \varepsilon_{i,s})$ is defined as the firm-specific return of stock i in week s .

Based on the above indicators, the variables *NCSKEW* and *DUVOL* are constructed to reflect the crash risk of stock i in year t :

$$NCSKEW_{i,t} = -\frac{n(n-1)^{\frac{3}{2}} \sum W_{i,t}^3}{(n-1)(n-2)(\sum W_{i,t}^2)^{\frac{3}{2}}} \quad (2)$$

$$DUVOL_{i,t} = \ln \frac{(n_u - 1) \sum_d W_{i,t}^2}{(n_d - 1) \sum_u W_{i,t}^2} \quad (3)$$

where n represents the number of weeks stock i was traded that year. In Eq. 3, n_u is the number of weeks in which the return rate of stock i is higher than the average weekly unique rate of return ($\overline{W_{i,s}}$). In the same way, n_d presents the number of weeks in which the return rate of stock i is below $\overline{W_{i,s}}$. The larger the value of *NCSKEW* and *DUVOL* is, the more inclined the return distribution is to the left, indicating that the risk of a stock price crash is higher.

3.2.2 Independent variable

Environmental Information Disclosure. The disclosure of environmental protection targets in the Environmental Research Database of CSMAR China Listed Firms is selected as the proxy variable for environmental information disclosure. If the environmental protection targets are disclosed by enterprises, the value is 1; otherwise, it is 0. Hao and Su (2014) pointed out that whether to disclose important information is an important way to measure information in existing studies. In view of this, some scholars take the binary variable of whether to disclose relevant information as the measurement method of environmental information disclosure (Tao et al., 2020). This paper draws on its ideas and selects whether to disclose environmental protection goals as a proxy variable for environmental information disclosure.

3.2.3 Mechanism variables

Media coverage (*media_t*). For each listed firm, the number of times the company's stock name appears in news search engines is counted according to the year, and the corresponding number of news reports is output and processed by logarithm.

3.2.4 Control variables

Based on the literature, the following variables are selected for control: market return (*ret_t*), market volatility (*sigma_t*), stock turnover rate (*turn_t*), current negative skewness return coefficient (*NCSKEW_t*), return on total assets (*roa_t*), audit quality (*big4_t*), operating revenue growth rate (*growth_t*), share ratio of the largest

shareholder (*first_t*), book to market ratio (*mb_t*), firm size (*size_t*), corporate transparency (*abacc_t*), and debt asset ratio (*lev_t*). Specific variable definitions are shown in Table 1.

3.3 Model specification

To explore the impact of information environmental disclosure on stock price crashes, this paper refers to the common practice of the literature of delaying all independent variables by one period and constructs the following model:

$$NCSKEW_{i,t+1} = \alpha_1 + \beta_1 CEID_{i,t} + \gamma_1 Controls_{i,t} + \sum Year + \sum Ind + \sum Prov + \varepsilon_{i,t} \quad (4)$$

$$DUVOL_{i,t+1} = \alpha_2 + \beta_2 CEID_{i,t} + \gamma_2 Controls_{i,t} + \sum Year + \sum Ind + \sum Prov + \varepsilon_{i,t} \quad (5)$$

where the dependent variables are the negative skewness coefficient of the return rate (*NCSKEW*) and the fluctuation of the return rate (*DUVOL*) in period $t+1$. The higher the value, the higher the risk of stock price crashes. The right side shows the independent variables in period t . This paper focuses on the significance level of β . Controls include all the control variables in Table 1. Additionally, year and industry are controlled. In addition, considering that the environmental information disclosure of enterprises will be affected by the environmental quality status and environmental protection policies of different provinces, this paper also controls the province dummy variable.

To explore the mediating effect of analyst attention and media coverage, the following model was constructed by referring to the three-step method proposed by Baron and Kenny (1986):

$$NCSKEW_{i,t+1} = \alpha_1 + \beta_1 CEID_{i,t} + \gamma_1 Controls_{i,t} + \sum Year + \sum Ind + \sum Prov + \varepsilon_{i,t} \quad (6)$$

$$DUVOL_{i,t+1} = \alpha_2 + \beta_2 CEID_{i,t} + \gamma_2 Controls_{i,t} + \sum Year + \sum Ind + \sum Prov + \varepsilon_{i,t} \quad (7)$$

$$media_{i,t} = \alpha_3 + \beta_3 CEID_{i,t} + \gamma_3 Controls_{i,t} + \sum Year + \sum Ind + \sum Prov + \varepsilon_{i,t} \quad (8)$$

$$NCSKEW_{i,t+1} = \alpha_4 + \beta_4 CEID_{i,t} + \delta_1 media_{i,t} + \gamma_4 Controls_{i,t} + \sum Year + \sum Ind + \sum Prov + \varepsilon_{i,t} \quad (9)$$

$$DUVOL_{i,t+1} = \alpha_5 + \beta_5 CEID_{i,t} + \delta_2 media_{i,t} + \gamma_5 Controls_{i,t} + \sum Year + \sum Ind + \sum Prov + \varepsilon_{i,t} \quad (10)$$

3.4 Summary

Table 2 reports descriptive statistics for the full sample. As shown in Table 2, the mean values of *NCSKEW* and *DUVOL* are -0.226 and -0.0857 , and the standard deviations are 0.660 and 0.458 , respectively. The mean value of the core explanatory variable Environmental Information Disclosure (*CEID*) is 0.1 .

TABLE 4 Mechanism analysis.

Media coverage					
	(1)	(2)	(3)	(4)	(5)
Variables	$media_t$	$NCSKEW_{t+1}$	$DUVOL_{t+1}$	$NCSKEW_{t+1}$	$DUVOL_{t+1}$
$CEID_t$	0.294***	−0.063***	−0.035**	−0.057**	−0.032**
	(0.063)	(0.023)	(0.016)	(0.023)	(0.016)
$media_t$				−0.019***	−0.011***
				(0.004)	(0.003)
Controls	Yes	Yes	Yes	Yes	Yes
Constant	−0.603	0.181	0.465***	0.170	0.459***
	(0.482)	(0.179)	(0.119)	(0.179)	(0.119)
Year	Yes	Yes	Yes	Yes	Yes
Ind	Yes	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes	Yes
Observations	9,165	9,165	9,165	9,165	9,165
R ²	0.1905	0.0937	0.1403	0.0959	0.1419
Bootstrap (reps = 500)				−0.007***	−0.002*
				(0.002)	(0.001)
Sobel Z value				−3.931***	−1.995**

Note: *, **, and *** indicate significance at 10, 5 and 1% level, respectively.

4 Analysis of empirical results

4.1 Environmental information disclosure and stock price collapse: A basic regression test

Table 3 reports the regression results of environmental disclosure and stock price collapse. Taking Column (3) and Column (4) as examples, regardless of whether $NCSKEW_{t+1}$ or $DUVOL_{t+1}$ is taken as the dependent variable, the coefficients of environmental information disclosure are −0.063 and −0.035, respectively, which are significant at the 1% and 5% statistical levels, respectively. This illustrates that compared with enterprises without environmental information disclosure, environmental information disclosure reduces the risk of a stock price crash, and the probability of such a crash decreases by 6.3% and 3.5%, respectively. There is a negative relationship between corporate environmental information disclosure and stock price overvaluation, indicating that the corporate disclosure of environmental goals can significantly reduce the risk of stock price crashes, which verifies [Hypothesis 1](#).

4.2 Mechanism analysis

The empirical results above show that corporate information disclosure can reduce the risk of stock price crashes. Then, as the key information intermediaries in the capital market, what role do analysts and media play in the above effects? Therefore, this paper uses the three-step method to analyze whether corporate environmental information disclosure has an impact on stock price crash risk through the mediating role of analyst attention and media attention.

Table 4 reports the mediating effect test results of media coverage. Column 1) tests whether environmental information disclosure has a significant impact on the mediating variable media attention, and the coefficient of $media_t$ is 0.294, which is significant at the 1% level. The results show that environmental information disclosure significantly promotes an increase in media attention, which increases the probability by 29.4%. Columns (2) and (3) show the regression results of the benchmark model. Columns (4) and (5) report the regression results of a stock price crash on environmental information disclosure and media attention. The regression coefficient of environmental information disclosure is significantly negative, and the regression coefficient of media attention is also significantly negative. At the same time, the coefficient signs (positive and negative) meet the requirements of the intermediary effect, excluding the masking effect. In addition, to ensure the rigor of the results, the Sobel test and bootstrap test were conducted. The Z values of the Sobel test were −3.931 and −1.995, respectively, which were significant at the 1% and 5% levels, and the indirect effects of the bootstrap test were significant at the 1% and 10% levels, respectively. In conclusion, there is a partial mediating effect of media attention on the negative relationship between environmental information disclosure and stock price crash risk, and the proportion of the total effect size is 8.87% ($NCSKEW_{t+1}$) and 9.24% ($DUVOL_{t+1}$), respectively, which confirms [Hypothesis 2](#).

4.3 Robustness tests

4.3.1 Instrumental variable method

The purpose of this paper is to investigate the causal relationship between environmental information disclosure and stock price crash

TABLE 5 IV-test.

Variables	First-stage	Seconde-stage	
	(1)	(2)	(3)
	$CEID_t$	$NCSKEW_{t+1}$	$DUVOL_{t+1}$
IV	0.993*** (0.013)		
$CEID_t$		-0.079** (0.035)	-0.040* (0.024)
Controls	Yes	Yes	Yes
Constant	-0.243*** (0.065)	0.178 (0.180)	0.465*** (0.121)
Year	Yes	Yes	Yes
Ind	Yes	Yes	Yes
Province	Yes	Yes	Yes
Observations	9,165	9,165	9,165
R ²	0.4309	0.0936	0.1403
Fist stage F value	58.33		
Cragg-Donald Wald F	6305.813		
Anderson-Rubin Wald		5.09 ($p = 0.0241$)	2.81 ($p = 0.0937$)

Note: *, **, and *** indicate significance at 10, 5 and 1% level, respectively.

risk. Although all explanatory variables are lagged by one period, the endogeneity problem may not be completely excluded. First, companies have the motivation to disclose environmental information for the purpose of improving their reputational capital and reducing the risk of stock price crashes, resulting in reverse causality. Second, the analysis of this paper may ignore some factors that are difficult to measure, such as system construction and policy support, which inevitably lead to the omission of variables. Therefore, this paper refers to the practice of (Ye et al., 2015) and chooses the industry mean ($\overline{CIED}$) of environmental information disclosure in the same region (province) in the same year as the instrumental variable of environmental information disclosure ($CEID$). Instrumental variables need to satisfy both correlation and exogeneity conditions. On the one hand, according to relevant studies, corporate environmental information disclosure has the same group effect, indicating that the level of information disclosure at the industry level will inevitably affect the information disclosure decision at the company level, ensuring that the original endogenous explanatory variables and instrumental variables have a strong correlation. On the other hand, the mean of environmental information disclosure in the same industry ($\overline{CIED}$) is less likely to directly affect the stock price crash risk of individual enterprises, which ensures the exogeneity of this instrumental variable.

Table 5 reports the regression results of the instrumental variables. In the first-stage regression, the regression coefficient of the mean value of the environmental information disclosure industry is 0.993, which is significant at the 1% level, indicating that the instrumental variables are highly correlated with the endogenous explanatory variables. The F value in the first stage was 58.33, much

greater than 10, which excluded the null hypothesis of “weak instrumental variables”. According to the two-stage regression results, the regression coefficient of environmental information disclosure is significantly negative, which is consistent with the basic regression, proving that the results of this paper are robust. In addition, this paper also reports a more stringent Anderson-Rubin Wald test, which rejects the null hypothesis that the sum of endogenous regression coefficients is equal to 0 at the significance level of 5% and 10%, respectively, which further illustrates the strong correlation between instrumental variables and endogenous explanatory variables.

4.3.2 Propensity score matching

Due to the differences in the characteristics of different enterprises, it is impossible to exclude the possibility that the two types of samples (with and without environmental information disclosure) show different stock price crash risks due to the inherent characteristics of enterprises, resulting in sample selection bias. For example, the mean size ($size = 22.61$) of sample firms that disclose environmental information is greater than that of firms that do not disclose environmental information ($size = 22.15$). The literature has confirmed that firm size is negatively correlated with the risk of stock price crashes. Therefore, to overcome the problem of sample selection bias, this paper adopts the propensity score matching (PSM) method to re-estimate the sample. Heckman et al. (1997) noted that for the selection of covariates in the first stage of the propensity score matching method (PSM), the inclusion of a small number of irrelevant variables has little impact on the results, but the omission of variables may cause serious bias. Therefore, to reduce artificial selectivity errors, all covariates in Table 2 were included in the model, and logit regression was used to calculate propensity score values. To save space, the first-stage regression results are not listed.

In Table 6, the ATT results obtained by using the four matching methods are all negative, and the T values are all greater than 1.96 (5% significance level), indicating that environmental information disclosure still significantly inhibits the risk of stock price crashes after considering the sample selection bias, which proves that the results obtained in this paper are robust.

4.3.3 Substitution variable

This paper uses the following two methods to measure the risk of stock price crash.

- (1) Referring to the method of Callen and Fang (2015), the stock price crash risk is measured by the difference between the frequency of downward and upward occurrence of the weekly specific return rate of a company's stock. The calculation process is as follows:

First, the weekly specific return rate in the downward phase is defined as:

$$crash_{down} = 1 [\exists s, W_{i,s} \leq \text{Average}(W_{i,s}) - 3.09\sigma_{i,s}] \quad (11)$$

where, $1[\cdot]$ is the indicator function, indicating that when stock i satisfies the above inequality in week s , the value of the variable is 1; otherwise, it is 0. $\sigma_{i,s}$ represents the standard deviation of the stock s week specific return ($W_{i,s}$), and the standard deviation of 3.09 corresponds to the region, where the probability of normal distribution is less than 1%.

TABLE 6 PSM Results.

Variables	Methods		Treatment	Control	ATT	Sd	Tvalue
$NCSKEW_{t+1}$	Unmatched		−0.3164	−0.2163	−0.1001	0.0229	−4.37
	Matched	neighbor	−0.3164	−0.2613	−0.0551	0.0255	−2.16
		caliper	−0.3158	−0.2494	−0.0664	0.0236	−2.81
		neighbor caliper	−0.3158	−0.2613	−0.0545	0.0255	−2.14
		Core	−0.3164	−0.2367	−0.0797	0.0234	−3.40
$DUVOL_{t+1}$	Unmatched		−0.1320	−0.0806	−0.0514	0.0159	−3.23
	Matched	neighbor	−0.1320	−0.0954	−0.0396	0.0174	−2.10
		caliper	−0.1315	−0.0919	−0.0396	0.0160	−2.48
		neighbor caliper	−0.1315	−0.0955	−0.0360	0.0174	−2.07
		Core	−0.1320	−0.0871	−0.0449	0.0159	−2.83

Note: *, **, and *** indicate significance at 10, 5 and 1% level, respectively. In order to enhance the reliability of the research results, this paper selected: ① nearest neighbor matching (k = 5) ② caliper matching (caliper = 0.01) ③ nearest neighbor caliper matching (k = 5; caliper = 0.01) ④ core matching (default kernel function and bandwidth).

TABLE 7 Substitution variable.

Variables	1)	2)	3)	4)	5)	6)
	$CRASH_{i,t+1}$	$CRASH_{i,t+1}$	$\overline{NCSKEW}$	$\overline{NCSKEW}$	$\overline{DUVOL}$	$\overline{DUVOL}$
$CEID_t$	−1.079***	−0.826***	−0.077***	−0.058***	−0.037***	−0.032**
	(0.281)	(0.280)	(0.020)	(0.020)	(0.014)	(0.014)
Controls	No	Yes	No	Yes	No	Yes
Constant	−41.893***	−38.946***	−0.406***	0.444**	−0.133**	0.558***
	(1.118)	(2.320)	(0.089)	(0.173)	(0.053)	(0.117)
Year	Yes	Yes	Yes	Yes	Yes	Yes
Ind	Yes	Yes	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes	Yes	Yes
Observations	6,358	6,358	4,347	4,347	4,347	4,347
R ²	0.3470	0.3578	0.0668	0.0946	0.1184	0.1416

Note: *, **, and *** indicate significance at 10, 5 and 1% level, respectively.

TABLE 8 Environmental information disclosure and board characteristics.

Variables	Low proportion of independent directors		High proportion of independent directors	
	$NCSKEW_{t+1}$	$DUVOL_{t+1}$	$NCSKEW_{t+1}$	$DUVOL_{t+1}$
$CEID_t$	−0.076**	−0.039*	−0.043	−0.030
	(0.031)	(0.021)	(0.038)	(0.025)
Controls	Yes	Yes	Yes	Yes
Year&ind&prov	Yes	Yes	Yes	Yes
Observations	5,025	5,025	3,926	3,926
R ²	0.1019	0.1463	0.1061	0.1687

Note: *, **, and *** indicate significance at 10, 5 and 1% level, respectively.

Similarly, the weekly specific rate of return in the upward phase is defined as:

$$crash_{up} = 1 [\exists s, W_{i,s} > Average(W_{i,s}) + 3.09\sigma_{i,s}] \quad (12)$$

Finally, the frequencies of $Crash_{down}$ and $Crash_{up}$ of stock i in year t are successively counted, and the difference between the two frequencies ($count_{i,t}(crash_{down}) - count_{i,t}(crash_{up})$) is obtained. The result is expressed as $CRASH_{i,t}$; the larger the value is, the higher the probability of a stock price crash.

- (2) Referring to the research of (Bennett B et al., 2020) the mean of the sum of the next three periods of the explained variables ($\overline{NCSKEW} = (NCSKEW_{t+1} + NCSKEW_{t+2} + NCSKEW_{t+3})/3$) is taken as a surrogate variable to measure the risk of a stock price crash. Considering that the future stock price crash risk will not affect the current information disclosure level, this method can somewhat avoid the endogeneity problem caused by reverse causality.

Columns (1) and (2) in Table 7 report the regression results of another calculation method $CRASH_{i,t+1}$. Columns (3)–(6) report the regression results of the mean values ($\overline{NCSKEW}$ and $\overline{DUVOL}$) in the next three periods. In this table, Columns (1), (3) and (5) do not add control variables. The remaining columns are the results of adding control variables. It can be seen that the sign of the core explanatory variable in this paper does not change after the addition of control variables, and the results of stock price crash risk measured in any way are significantly negative, proving that the results of this paper are robust.

5 Further analysis

5.1 Does environmental information disclosure have a supervisory effect?

According to agent theory, if the internal supervision level of the enterprise is weak, there is a higher probability that management will negative news out of self-interest, exacerbating the risk of stock price crashes. Then, as a type of non-financial information disclosure, does environmental information disclosure have an inherent supervisory effect and reduce principal-agent problems? that is, does it play a role in reducing the risk of stock price crashes by reducing the likelihood that executives will hide negative news? To answer the above questions, we reference the ideas of Zhu et al. (2020), and the proportion of independent directors of a company is selected as a proxy variable for the characteristics of the board of directors for the group test. The logic is as follows: the board of directors system is the basis for the supervision of the management of listed companies. If the proportion of independent directors is low, it means that the company's senior executives have more rights and less resistance to pursuing egotistical goals; in this case, the probability of hiding negative news increases, which leads to agency problems and increases the risk probability of stock price crashes. If environmental information disclosure has a supervisory effect on company executives, it should be a powerful supplement to the management of the company as independent directors. Therefore, we focus on whether environmental disclosure can play a complementary role when independent directors fail to implement

effective supervision. In other words, does environmental information disclosure have a stronger effect on reducing the risk of stock price crashes for companies with a low supervision effect of independent directors?

According to whether the proportion of independent directors of listed firms is greater than the annual industry median, the samples are divided into two categories: a high proportion of independent directors and a low proportion of independent directors. According to Table 8, for firms with a high proportion of independent directors, the regression coefficients of stock price crash risk $NCSKEW_{t+1}$ and $DUVOL_{t+1}$ on environmental information disclosure $CEID_t$ are not significant. In contrast, in the group with a low proportion of independent directors, the regression coefficients of environmental information disclosure are significant at the 5% and 10% levels. The above results show that when the proportion of independent directors is low, environmental information disclosure can reduce the risk of stock price crashes. In other words, environmental information disclosure can be used as an effective supplement to the internal supervision of the company.

5.2 Is environmental information disclosure a resource competition tool?

Although the above analysis does not distinguish between the motivations for environmental information disclosure, but the actual effect of environmental actions implemented by enterprises may vary greatly depending on the different motivations. Previous studies have shown that the motivations for enterprise information disclosure are restricted by industry competition (Stivers, 2004). In fierce market competition, enterprises will fully disclose information to compete for limited resources in the capital market, improve the transparency of corporate information and reduce the cost of capital. In this case, if the competition for resources as the motivation for a company to disclose environmental information is low compared to the competition in the industry, the company in the highly competitive industry will not only increase its environmental information disclosures but will also enrich the contents of the disclosure. Such improvements in the quality of the environmental information disclosure and increases in the transparency of information can effectively reduce stock crash events.

Based on the above considerations, the division is conducted according to the median Herfindahl-Hirschman index (HHI_MEDIAN) of the overall annual industry. If higher than HHI_MEDIAN , the competition pressure of the industry is low. Otherwise, it means higher competitive pressure in the industry. Table 9 reports the empirical results. The regression coefficients of stock price crash risk and environmental information disclosure measured by $NCSKEW_{t+1}$ are -0.069 in the low-competition industry and -0.066 in the high-competition industry, both of which are significant at the 5% significance level. The regression coefficients of $DUVOL_{t+1}$ on environmental information disclosure measured by stock price crash risk are -0.044 and -0.034 , respectively. Although the coefficient in the last column is not significant, on the whole, no matter how the stock price crash risk is measured, environmental information disclosure has a more significant effect on reducing the stock price crash risk in low-competition industries, indicating that environmental information disclosure is not a self-interested tool for companies to compete for resources.

TABLE 9 Motivation of environmental information disclosure.

Variables	Low industry competitive pressure		High industry competitive pressure	
	$NCSKEW_{t+1}$	$DUVOL_{t+1}$	$NCSKEW_{t+1}$	$DUVOL_{t+1}$
$CEID_t$	-0.069**	-0.044*	-0.066**	-0.034
	(0.035)	(0.023)	(0.031)	(0.021)
Controls	Yes	Yes	Yes	Yes
Year&ind&prov	Yes	Yes	Yes	Yes
Observations	4,352	4,352	4,813	4,813
R ²	0.0840	0.1495	0.1127	0.1429

Note: *, **, and *** indicate significance at 10, 5 and 1% level, respectively.

5.3 Environmental information disclosure, institutional investor shareholding and stock price crash risk

According to stakeholder theory, the enterprise is an institutional arrangement of specialized investment in intelligence and management. The survival and development of the enterprise depend on the quality of the enterprise's response to the interest requirements of various stakeholders, not just on shareholders. The above analysis does not consider the reaction of other stakeholders to environmental information disclosure. As important shareholders of companies, institutional investors have attracted increasing attention regarding the impact of stock price crash risk. Therefore, this paper analyzes the impact of other stakeholders' reactions on new environmental information disclosure from the perspective of institutional investors, which not only helps us understand the role of other stakeholders in "environmental information disclosure-stock price crash risk" from the theoretical level but also provides a reference for regulators to specify relevant decisions. The existing literature has shown that institutional investors affect the relationship between environmental information disclosure and stock price crashes from at least two paths. 1) The motivation of governance. With the increase in the shareholding ratio of institutional investors, the motivation of institutional investors to carry out active behaviors is enhanced, which makes institutional investors carry out supervision and governance behaviors to avoid the benefit loss caused by information asymmetry. Existing studies show that institutional investors have governance effects on the quality of corporate information disclosure (Aggarwal et al., 2011), which can improve the accuracy, timeliness and robustness of information disclosure, thereby increasing information transparency and reducing the risk of stock price crashes. Therefore, from the perspective of governance motivation, we believe that an increase in the shareholding ratio of institutional investors will promote the negative effect of new environmental information disclosure on the risk of stock price crashes. 2) Profit motive. Jiang and Kim (2015) pointed out that institutional investors in China have a significant short-term investment tendency. This means that environmental information disclosure may become a tool for institutional investors to make profits; that is, by increasing the number of disclosures or exaggerating positive news, investors will overreact to information and make wrong investment decisions, which will further promote short-term stock price bubbles. However, this type of bubble is not sustainable. As negative news enters the market, investors will panic, and the probability of stock prices falling sharply will increase,

TABLE 10 Analysis based on the perspective of institutional investors' shareholding ratio.

Variables	$NCSKEW_{t+1}$	$DUVOL_{t+1}$
$CEID_t$	-0.146***	-0.094***
	(0.053)	(0.035)
$CEID_t * ins_t$	0.002*	0.001*
	(0.001)	(0.001)
ins_t	-0.001**	-0.000**
	(0.000)	(0.000)
Controls	Yes	Yes
Year&ind&prov	Yes	Yes
Observations	4,352	4,352
R ²	0.0840	0.1495

Note: *, **, and *** indicate significance at 10, 5 and 1% level, respectively.

which eventually leads to a stock price crash. Therefore, from the perspective of profit motives, an increase in the shareholding ratio of institutional investors may inhibit the negative effect of environmental information disclosure on the risk of stock price crashes.

To verify the above problems, we introduce the interaction term between environmental information disclosure and the shareholding ratio of institutional investors, and Table 10 reports the results. It can be seen that the interaction term between the two is significantly positive, which is contrary to the sign of environmental information disclosure, reflecting that institutional investors' shareholding inhibits the negative effect of environmental information disclosure on stock price crash risk; thus, the above profit-motive hypothesis is verified.

5.4 Environmental information disclosure, government environmental governance and stock price crash risk

Finally, in view of the framework of "environmental information disclosure-stock price crash risk," this part conducts research by embedding the environmental governance elements of the government from a macro perspective. Referring to the research of (Chen and Chen, 2018), the total frequency of environmental words in provincial government work reports and the total frequency of words

TABLE 11 Based on the perspective of government environmental governance.

Environmental governance	Low		Median		High	
	$NCSKEW_{t+1}$	$DUVOL_{t+1}$	$NCSKEW_{t+1}$	$DUVOL_{t+1}$	$NCSKEW_{t+1}$	$DUVOL_{t+1}$
$CEID_t$	-0.063*	-0.036	-0.031	0.006	-0.082**	-0.064**
	(0.038)	(0.027)	(0.045)	(0.029)	(0.039)	(0.027)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Year&ind&prov	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3,382	3,382	2,763	2,763	3,020	3,020
R ²	0.1051	0.1586	0.1323	0.1836	0.1099	0.1487

Note: *, **, and *** indicate significance at 10, 5 and 1% level, respectively.

in the report were used to measure the intensity of government environmental governance. Based on the intensity of environmental governance, group processing was conducted (adopting 3 quantiles), and the regression test of Eq. 4 was conducted again. The empirical results are shown in Table 11. In the interval where the government has a high level of environmental governance, environmental information disclosure has a good inhibitory effect on the risk of stock price crashes (the coefficient is negative, and both pass the 5% significance level test). Taking the last case as an example, in regions with higher levels of external governance, compared with enterprises without environmental information disclosure, the probability that enterprises with environmental information disclosure can reduce the risk of stock price crashes in the next year is 6.4%. In the group with low and medium levels of governance, only the regression coefficient of stock price crash risk, measured by $NCSKEW_{t+1}$ on environmental information disclosure $CEID_t$, is significant. This indicates that a higher level of environmental governance is an important basic condition for environmental information disclosure to reduce the risk of stock price crashes.

6 Conclusion and policy recommendations

Taking Chinese A-share listed firms from 2013–2018 as the sample, this paper empirically tests the impact of environmental information disclosure on stock price crash risk. It is found that environmental information disclosure is significantly negatively correlated with estimated crash risk, and this result is still significant after using instrumental variables, propensity score matching (PSM), substitution variables and a series of other robustness tests. The mechanism analysis shows that media coverage has a mediating effect on the relationship between the two. Further analysis indicates that the characteristics of the board of directors, multilevel capital market, industry competition pressure, institutional investors' shareholding ratio and the level of government environmental governance are important factors affecting the relationship between "environmental information disclosure and stock price crash risk". This paper further opens the black box of non-financial information disclosure to improve the market information environment. The results also show that positive enterprise environmental information disclosure is not only beneficial to the construction of socialist ecological civilization but

also has the effect of reducing the risk of stock price crash "icing on the cake". It is of great practical significance to improve the information disclosure system, strengthen corporate governance, strengthen government environmental governance, and prevent systemic financial risks for regulatory departments and investors.

- (1) Improve the information disclosure system. It is necessary to further improve the effective and feasible standards for the public disclosure of environmental information, including the release of disclosure guidelines covering the content range and format of environmental information, and put forward more targeted and refined requirements for environmental information disclosure to provide reference standards for enterprises to implement environmental information disclosure. Strengthen the supervision of environmental disclosure, establish and improve the punishment mechanism, and avoid the occurrence of "more talk than action" in the aspect of environmental responsibility of enterprises, which is conducive to improving the integrity, authenticity and comparability of corporate information, facilitating the selection of stakeholders, and effectively playing the role of participants in the capital market with active concern motivation in information intermediaries.
- (2) News, newspapers and other media should be proactive and give full play to their role as an information intermediary. On the one hand, it is necessary to continuously explore and pay attention to the environmental information disclosed by enterprises, increase the exposure of enterprises' environmental protection behaviors, attract the attention of external stakeholders to give enterprises greater pressure on environmental responsibility, and urge enterprises to disclose more valuable information. On the other hand, we should consider increasing the publicity of enterprises that earnestly fulfill their environmental responsibility, enhancing investors' perception of such enterprises, providing potential impetus for enterprises to continue to implement environmental protection behaviors, making full use of the power of public opinion to form an environmental atmosphere in the whole society, and laying a solid foundation for the construction of ecological civilization.
- (3) Regulatory authorities should focus on strengthening financial supervision, standardizing the financial supervision system, effectively improving the quality of environmental information disclosure of enterprises, and alleviating the adverse impact of the accumulation of stock price crash risk caused by the concealment of "bad news" by senior executives. On the one hand, it is

necessary to continuously strengthen functional financial supervision, attach importance to and standardize the content and system of non-financial information disclosure of enterprises, take non-financial information disclosure systems as an effective supplement to the total loss absorption capacity supervision system, and jointly serve the stability construction of the Chinese capital market. On the other hand, for different market sectors and industry types, regulatory authorities can implement differentiated management policies. The results of this paper show that the impact of environmental information disclosure on stock price crash risk varies by sectors and industries under different competitive pressures, indicating that the “one-size-fits-all” regulatory scheme does not reflect the actual needs of different types of enterprises, so specific regulatory measures should be formulated for enterprises with different attributes. We should ensure that the capital market can better serve the development of the real economy through appropriate forecasting and classified intervention.

- (4) For the government, it is necessary to continuously improve the level of environmental governance, lay a good foundation for enterprises to assume environmental responsibility and timely disclosure, make reasonable use of administrative means, and form a scientific, environmental governance system dominated by the government and enterprises. It is necessary to make good use of market-oriented means to give publicity, tax and preferential policies to those enterprises that actively undertake environmental protection responsibilities, send positive signals to the market, attract the attention of investors in the capital market and bring capital inflow, and provide a potential impetus for enterprises to actively undertake environmental protection responsibilities and improve environmental protection information disclosure.

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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

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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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Collectivism culture and green transition: An empirical investigation for the rice theory

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With growing concerns worldwide on global warming, emissions reduction has become a major challenge for many countries. China, as the largest carbon emitter, has played a key role in achieving global green transition. Using panel data from 2004–2017 on 31 Chinese provinces, this study examines the relationship between the collectivism culture and green transition. My results reveal that places with a stronger collectivism culture tend to make more green investments, and the results remain valid after a battery of robustness tests. In addition, the heterogeneity analysis indicates that the positive effects of collectivism culture on green investments are more pronounced if the province governor is advanced in age, well educated, and holds a long tenure. Additionally, such effects are more conspicuous in those provinces with more serious pollution, greater levels of collectivism, and more developed markets. This study fills a theoretical gap in the field of research on green investments from a cultural perspective. Therefore, this study has important implications for promoting green development and achieve carbon peaking and neutrality.

KEYWORDS

collectivism culture, green transition, the rice theory, environment governance, emerging markets

1 Introduction

Global warming caused by carbon emissions has become an issue of worldwide concern (Chen et al., 2022), and it poses a serious threat to human development (Yu et al., 2022). The main reason for the increase of such emissions is human activities (Pachauri and Meyer, 2014; Tong et al., 2022; Wang et al., 2023). At the 2015 Paris Climate Conference, China, as the largest carbon emitter (Kang et al., 2022), proposed as its 'Intended Nationally Determined Contributions' to reach peak carbon emissions around 2030, pledging that it would do its utmost to achieve this goal (Chen, 2022). In 2020, China put forward the goal of 'peak carbon emissions and carbon neutrality', which drew widespread attention both at home and abroad. The government and the public have increasingly high requirements for environmental protection (Tian et al., 2022a). However, some projections regarding the country's greenhouse gas emission trends under its current policies indicate that emissions will peak at 113–118 million tonnes in 2030. Judging from its current national carbon reduction policies, there is a likelihood that China will miss this goal, for which stronger policy measures will be needed (Elzen et al., 2016). Thus, it is clear that China is still facing a huge challenge regarding carbon emission reduction.

As global economic growth and carbon emissions increase as a result of consumption and production processes, the role of investment in promoting and controlling carbon emissions becomes particularly important. From 2016 to 2030, Asia will need to invest

roughly \$1.7 trillion per year, or about \$26 trillion cumulatively regarding the issues of eradicating poverty, sustaining growth, and addressing climate challenges. Of these estimated investments, approximately \$14.7 trillion is needed for electricity, \$8.4 trillion for transportation, \$2.3 trillion for telecommunications, and \$0.8 trillion for water and sanitation (Sachs et al., 2019). Countries are focusing on building efficient energy systems to move towards a low-carbon economy (Tian et al., 2022b; Tao et al., 2022). This transition will require green financing and the pricing of externalities. However, carbon pricing will not be sufficient to address environmental sustainability challenges. According to International Monetary Fund estimates, carbon pricing levels are not commensurate with the requirements to mitigate global environmental problems (Lagarde and Gaspar, 2019). Public investment in the form of green financing plays a key role in reducing greenhouse gas (GHG) emissions, creating efficient energy systems, and building robust climate markets (Mazzucato, 2016).

Among the various macroeconomic factors deemed to be affecting carbon emissions, previous studies have specifically mentioned green investments (Krushelnyska, 2017), which are investments into industrial pollution controls in a bid to mitigate environmental pollution (Li et al., 2020). Studies have demonstrated that green investment is a key factor in reducing carbon emissions and promoting sustainable growth. Furthermore, research has considered green investments mainly from the corporate perspective (Wan et al., 2021; Liu et al., 2022a; Liu et al., 2022b). Many factors, including external and internal ones, can influence green investments. Market competition is a major external factor (Rui and Lu, 2021), whereas internal factors include enterprise properties (Huang and Lei, 2021), managerial characteristics (Jang et al., 2017; Jia et al., 2021), and corporate culture (Fiordelisi et al., 2019). On the government side, research indicates that administrations could promote green investments by setting environmental regulations (Huang and Lei, 2021) and providing subsidies (Jung and Feng, 2020). However, relatively little research has been conducted on the impact of culture on green investments.

Collectivism culture is characterised by mutual protection among individuals through the formation of close team relationships and individuals' loyalty to the collective interest. According to Hofstede (1980) and Bhagat (2002), individual goals in collectivism culture are established in the interest of the team as a whole. When an individual's opinion diverges from that of a larger community, they tend to avoid any conflicts that could arise from the expression of a different opinion. As a result, individuals are less likely to voice their own interests. However, in an individualistic culture, relationships between people are more tenuous and individuals are given the responsibility of looking after themselves and their own families. Employees' value and their organisation's perception of them can be reflected through the allocation of resources; as a result, employees will pay attention to achievement and personal gain in their work. These two cultures, collectivism and individualism, can influence people's tendency to engage in environmental behaviour in different ways. On the one hand, the former tends to prompt people to consider the impact of individual behaviour on others. Therefore, the behaviour of collectivists tends to be driven by social norms, and these people

are shown to be more willing to share scarce resources. On the other hand, the latter tends to promote contractual relationships based on the principle of exchange, on the basis of which people calculate profits and losses before engaging in a certain behaviour. Individualists place greater importance on the relationship between their action and their needs and beliefs. With individualism, one tends to focus one's attention on the immediate benefits relative to the costs (Yuan, 2020). However, extrinsic benefits could be scant in the short term relative to perceived costs.

Recent developments in rice culture and its methodology (Talhelm et al., 2014, 2018) have enabled people to measure the differences between collectivist and individualist cultures. The rice theory suggests that people in areas with a longer history of rice cultivation are more collectivist than those in wheat-producing areas. The reason for this is that growing rice requires more intensive irrigation and labour than growing wheat. Therefore, a rice farmer needs more cooperation with family members and agricultural workers living in the vicinity.

In this study, I use the rice theory to examine collectivism culture and its impact on government green investments. Specifically, I argue that provincial governors with collectivist tendencies make more green investments than those with individualist leanings. I empirically examine the impact of provincial leaders' collectivist tendencies on green investments in China. Examining Chinese provincial administrative regions over the period 2004–2017, I determined whether collectivist governors made more green investments. I used the scale of rice cultivation to measure the degree of collectivism culture in the governor's birthplace. Specifically, I constructed a proxy variable for collectivism culture, namely the percentage of rice cultivation (*Rice*) in the province where the leader was born. I argue that collectivism culture is stronger in areas with a higher percentage of rice cultivation (Talhelm et al., 2014). I expect the culture to be the dominant culture in areas where rice cultivation is the prevailing agricultural activity. The findings suggest that such culture has a significantly positive impact on government green investments.

Further analysis reveals that the relationship between collectivism culture and government green investments is influenced by governors' disposition and regional characteristics. First, the positive relationship between collectivism culture and green investments is more significant when the governor is older than 57, has a higher level of education (postgraduate and above), and holds a longer term of office. Second, the positive relationship is more significant when the region has stronger collectivism culture, a higher level of marketization, and a higher degree of environmental pollution.

This research makes the following contributions. First, I examine green investments from a cultural perspective. I provide evidence that provincial governors' pro-environmental attitudes arise through a collectivist propensity and can influence green investments. Second, this study fills a gap in current research by investigating the impact of culture on green investments from a governmental perspective, thereby broadening the scope of environmental sustainability studies. Third, this study expands the possibility of rice theory application. My use of the theory to measure collectivism could provide some insight into how to broaden the scope of applying a classical theory to solve practical problems.

The rest of the paper is organised as follows. My research hypotheses are presented in Section 2, and my research design is detailed in Section 3. The results with baseline regression, endogenous analysis, robustness tests and heterogeneity issues are reported in Section 4. Finally, concluding remarks are presented in Section 5.

2 Background and hypotheses

2.1 Rice theory

Talhelm et al. (2014) determined that there are clear cultural differences between the south and north of China.¹ This is reflected in the fact that the south, where rice is grown, is more collectivist, while the north, where wheat is grown, is individualist. This led them to develop the rice theory. This theory argues that rice farming leads to collectivism culture, while wheat farming leads to an individualist culture. This is because growing rice requires intensive cooperation, while growing wheat does not. Over time, the two cultures took shape through farming activities and social interaction. Once the cultures were formed, they also had an impact on people who were not involved in agriculture. Talhelm et al. (2014) empirically demonstrate the link between rice cultivation and collectivism in China.

2.2 Collectivism culture and green investments

Collectivism culture emphasises the needs and goals of the group rather than those of the individual. One reason people are more interdependent in some societies is that group cooperation is more productive. For example, interdependence is more valuable in agricultural activities than in herding activities and over time, farmers become more inclined to collectivism than herders (Berry 1967; Nisbett et al., 2001). Some research suggests that collectivism culture can influence a person's behaviour through self-identity, which is their internal construct of the self. Thus, collectivism culture influences individuals from within, which in turn influences their green investment behaviour. Collectivism culture shapes individual values and can directly influence green investments. In addition, the conservative disposition of individuals with a collectivist tendency influences investment preferences, which in turn affects green investments.

Because culture has a significant impact on people's values, collectivism can directly influence the environmental preferences of provincial governors, which will then have an impact on green investments. According to the values-beliefs-norms theory, individuals with strong environmental values are likely to be aware of the consequences of environmental problems, adopt responsible environmental behaviour, and participate in or support environmental action (Stern et al., 1999; Stern, 2000).

The theory of planned behaviour (TPB) (Ajzen, 1991) also explains the relationship between values and behaviour. This theory suggests that individuals' beliefs and attitudes towards a particular behaviour determine their intention to engage in that behaviour. Research on the psychological determinants of pro-environmental behaviour suggests that personal values are an important factor in an individual's commitment to pro-environmental behaviour (Nordlund and Garvill, 2002). Kaplan Mintz and Kurman (2020) selected recycling from pro-environmental behaviours to examine the relationship between such behaviour and collectivism culture. The findings suggest that the collectivism culture facilitates individuals' recycling behaviour by influencing a person's belief in recycling.

2.3 Hypotheses

Through the above analysis, I have developed hypotheses about the relationship between collectivism culture and government green investments. I expect that governors born in provinces with stronger collectivism culture make more green investments.

3 Model setup and variable description

3.1 Benchmark regression

To verify the above hypotheses, I first construct the basic econometric model as follows.

$$\ln GI_{it} = \alpha_0 + \alpha_1 Rice_{it} + \beta X_{it} + \gamma_i + \mu_t + \varepsilon_{it} \quad (1)$$

Where i denotes province and t denotes year. The explained variable $\ln GI_{it}$ represents green investments. The explanatory variable $Rice_{it}$ measures the cultural value of rice in the governor's birthplace. X is a set of control variables including level of economic development (log), pollution emissions (log), intensity of environmental regulation (log), level of urbanisation (log), and governor characteristics (age, tenure, education). γ_i is the province fixed effect, controlling for any permanent differences between provinces, such as geographical characteristics and natural endowments. μ_t is the time fixed effect, capturing any unobserved year-specific effects, such as macroeconomic shocks, business cycles, and fiscal and monetary policies common to both planned and unplanned areas.

3.2 Selection of data and variables

This study uses panel data from 2004 to 2017 on 31 provincial-level administrative regions in China. I set the starting point for temporal observation as 2004 because there are limited sources of information on government officials prior to this. The information after this year is comprehensive and reliable. In the Chinese political system, the provincial party secretary is usually in charge of personnel affairs and the provincial governor is responsible for managing the provincial economy. As such, provincial governors play an important role in government green investments. Therefore, I have chosen data on provincial governors.

In addition, environmental and other economic indicators for each province were obtained from *China Urban Statistical Yearbook*,

¹ Distribution of rice culture in China can be seen in Figure 1 of Talhelm et al. (2014).

China Environmental Statistical Yearbook, and China Statistical Yearbook. Data on governors' tenure, age and other personal information were obtained from the China Leaders Database (<http://people.cn>), from which I gathered the CVs of 125 governors holding office from 2004 to 2017 and collected their information manually.

3.2.1 Explanatory variables

The collectivism culture is used as the explanatory variable. As culture is usually acquired during childhood, I use the prevailing culture of the governors' birthplace to capture their cultural origins. As children's minds are impressionable, such cultural imprints are easily remembered and retained (Hofstede and Hofstede, 2005). It is important to note that under China's hukou (household registration) system, a child's hukou location is registered as that of their parents. Some people may be concerned that if a child is born in City A and the parents' hukou is City B, then the child's hukou will be City B, which is different from the place of birth. This concern would be warranted if the child had been born after 1978. This is because population movements gradually became more frequent along with China's economic reform. However, the governors in the sample were all born in a time when migration was strictly limited (before 1978) (Chan and Zhang, 1999; Wu and Treiman, 2004). Therefore, misidentification of place of birth is not a main concern in this study. Following Talhelm et al. (2014), I use the level of rice cultivation in the region to measure the degree of collectivism culture in the governor's birthplace. Specifically, I construct a proxy variable ($Rice_{it}$) for collectivism culture, which is the percentage of rice cultivation in the province where the governor was born. I expect that collectivism culture is stronger in areas with a higher percentage of rice cultivation.

3.2.2 Explained variables

The green investments ($lnGI_{it}$) is used as the explained variable to reflect regional green transition. I expect that more green investments are made if degree of green transition is higher. Based on previous studies, green investments are investments into industrial pollution controls in a bid to mitigate environmental pollution (Li et al., 2020). Therefore, I use the data of 'completed investment in industrial pollution control' in provincial statistical yearbooks to measure the level of green investment in the province.

3.2.3 Control variables

Based on existing research, I selected a set of governor characteristics as control variables, including age (old), education (edu), and tenure (term). At the same time, I also take level of economic development (pgdp), pollution emission (so2), intensity of environmental regulation (sewage), and level of urbanisation (nub) of each province as control variables. In addition, year fixed effects (year) and province fixed effects (province) are controlled. The descriptive statistics of all variables used in the baseline regression are postponed to Appendix A.

4 Results and discussion

4.1 Results of the baseline regression

To examine the relationship between collectivism culture and green transition, I construct the basic econometric model 1). Results

of the Hausman test indicate that the fixed effects model outperforms the random effects model. The results of the baseline regressions are reported in Table 1. Column 1) presents estimates of the impact of the governor's collectivism culture on green investments in the province, along with control variables. Year fixed effects are added in Column 2), province fixed effects in Column 3), and both year and province fixed effects in Column 4). All estimates consistently demonstrate that collectivism culture of the governor has a significant positive impact on green transition. Collectivism culture emphasises the needs and goals of the group, and pays more attention to social responsibility. The attitudes towards environmental issues and investment preferences of regions with higher collectivism culture are more inclined to the aspects conducive to environmental protection. Therefore, collectivism culture has a positive impact on green transition.

4.2 Endogenous analysis

The share of rice fields in an area of cultivated land is a proxy variable for whether the culture favours collectivism or individualism, but there is still the problem of endogeneity caused by reverse causation. One way to address endogeneity is to identify instrumental variables, and a place's suitability for growing rice is considered to be a good instrumental variable for the share of rice fields (Caruso et al., 2016; Yuan, 2020). Generally speaking, whether rice is grown is closely related to elements such as water, temperature, and terrain. Therefore, this study uses precipitation and temperature in the province to measure rice cultivation suitability as an instrumental variable for the share of rice fields.

The results of the first stage regression are reported in Column 1) of Table 2. The instrumental variable is significantly and positively correlated with the explanatory variable at the 1% level. The second stage estimation results reported in Column 2) of Table 2 again indicate that the governor's collectivism has a significant positive impact on green investments in the province. Furthermore, the results of the Underidentification test, weak identification test and Hansen J statistic indicate that the instrumental variables do not suffer from weak instrumental variable problems and are both correlated and exogenous.

4.3 Robustness tests

To verify the robustness of the baseline regression results, I conducted the robustness test from the perspective of the influence of migration, of nomadic regions, of Confucian culture, and of the financial crisis and green credit policies. The results confirm the main findings of the fixed effects model and indicate that the empirical results remain highly stable.

4.3.1 Provincial governors from a border region separating rice and wheat cultivation

As a result of foreign invasions and civil wars, China has witnessed several large population migrations throughout its history, mostly from the north to the south. Although most occurred around 1000 years ago during the Song dynasty, after

TABLE 1 Baseline regression.

Variables	(1)	(2)	(3)	(4)
	lnGI	lnGI	lnGI	lnGI
Rice	0.0033***	0.0030***	0.0034***	0.0030***
	(0.0010)	(0.0009)	(0.0010)	(0.0010)
lnpgdp	0.6250***	0.6210***	0.6190***	0.3290
	(0.0871)	(0.1940)	(0.0942)	(0.2760)
lnso2	0.4060***	0.4240***	0.3290***	0.3170***
	(0.0591)	(0.0658)	(0.0851)	(0.1180)
lnsewage	0.4350***	0.4290***	0.3990***	0.4030***
	(0.0599)	(0.0618)	(0.0733)	(0.0712)
lnnub	−0.2250	−0.2960	−0.2930	−0.3310
	(0.2470)	(0.2940)	(0.3410)	(0.3450)
old	−0.0081	−0.0056	−0.0090	−0.0062
	(0.0070)	(0.0068)	(0.0073)	(0.0069)
edu	0.0039	0.0186	−0.0023	0.0191
	(0.0515)	(0.0485)	(0.0552)	(0.0514)
term	−0.0534***	−0.0390**	−0.0486***	−0.0348*
	(0.0163)	(0.0173)	(0.0182)	(0.0182)
Constant	0.5870	0.6820	1.6300	4.2850*
	(0.7900)	(1.2730)	(1.2160)	(2.3210)
Provinces FE	NO	NO	YES	YES
Year FE	NO	YES	NO	YES
Observations	424	424	424	424
R-squared	0.716	0.750	0.352	0.464

Notes: ***, **, and * represent significant at 1, 5, and 10% significance level, respectively; standard errors are provided in parentheses.

which descendants of these northern migrants became adapted to the local rice culture; these migrations still mixed-up rice, wheat, and other cultures and may have weakened the influence of regional cultures (Fan et al., 2022). To address this issue, I followed Jiang et al. (2019) and excluded provinces along the Qinling-Huaihe border (Sichuan, Chongqing, Hubei, Anhui, Guizhou, and Jiangsu) and conducted the robustness test. The results are shown in Column 1) of Table 3, where the signs of the *Rice* estimated coefficients are consistent with the assumptions made in the baseline regression and are significant at the 1% level.

4.3.2 Impact of nomadic regions

Although China has always been regarded as a country of crop cultivation, herding is still the main agricultural activity in Tibet, Xinjiang, and Inner Mongolia. Therefore, I re-ran the test after excluding governors from these pastoralist regions. The results are reported in Column 2) of Table 3, where the culture of collectivism among governors still has a significant positive impact on green investments in the province.

4.3.3 Influence of the Confucian values system

The Confucian values system has had a profound influence in China, which may also have led governors to make more green investments. If areas with more rice cultivation (i.e. areas with stronger collectivism culture) also have stronger Confucian values, the previous conclusion may also be due to such values rather than collectivism culture itself.

The system originated in Confucius' homeland of Shandong province, a wheat-producing region in northern China, and then gradually spread to the south as Han Chinese migrated from the north to the south. Since the Han dynasty (202 BC to 220 AD), dynastic rulers have used Confucian values to govern the country and its people, with this system becoming ever more entrenched during the Ming (1368–1644) and Qing (1644–1912) dynasties. The capital cities of the Han dynasty were Chang'an and Luoyang, and during the Ming and Qing dynasties, the capital was Beijing. These capital cities were located in wheat-producing areas. The Confucian values system was the most dominant in power centres and radiated to remote areas. Therefore, to assess and control for

TABLE 2 Endogenous analysis.

Variables	(1)	(2)
	First	Second
	Rice_culture	lnGI
humidity	3.2093***	
	(0.1795)	
temperature	1.0065***	
	(0.3051)	
Rice		0.0030*
		(0.0016)
lnpgdp	6.1771**	0.5612***
	(2.5301)	(0.1122)
lnso2	1.3699	0.3650***
	(1.4660)	(0.0848)
lnsewage	−2.2872	0.4602***
	(1.5252)	(0.0860)
lnnub	−3.8059	−0.1215
	(5.4378)	(0.3034)
old	0.2465	−0.0033
	(0.2168)	(0.0100)
edu	1.5985	0.1057
	(1.5717)	(0.0799)
term	2.1211***	−0.0436
	(0.5601)	(0.0374)
Constant	−265.6863***	0.3736
	(23.7875)	(1.2949)
Provinces FE	YES	YES
Year FE	YES	YES
Observations	427	424
R-squared	0.8318	0.7667

Notes: ***, **, and * represent significant at 1, 5, and 10% significance level, respectively; standard errors are provided in parentheses.

the potential impact of the Confucian values system, I measured the regional system using *CC*, a dummy variable equal to 1 if the founder was born in Shandong, Henan, Jiangsu, Shaanxi, or Zhejiang, and 0 otherwise. Shandong province is the hometown of Confucius and the birthplace of the Confucian culture. The latter four regions were home to ancient cities of the Han dynasty (202 BC to 220 AD), the Tang Dynasty (618–907) and the Song and Ming Dynasties (960–1911), respectively. The Confucian values system in these regions was significantly stronger than in other parts of China.

The regression results for Confucian culture are presented in Column 3) of Table 3. The measure of Confucian culture is not

statistically significant, while the coefficient of the proportion of rice field area is statistically significant. Therefore, I could not find any evidence that the relationship between rice cultivation and green investments is driven by Confucianism.

4.3.4 The financial crisis and the impact of green credit policies

I have considered the impact of the 2008 financial crisis and the green credit policy enacted in 2012. The financial crisis had a huge impact on the Chinese economy (Li et al., 2012) and also brought about greater pressure and changes in the appraisal of government officials. In addition, the green credit policy enacted in 2012 also

TABLE 3 Robustness tests.

Variables	(1)	(2)	(3)	(4)	(5)
	lnGI	lnGI	lnGI	lnGI	lnGI
Rice	0.0028***	0.0026***	0.0029***	0.0027***	0.0027***
	(0.0010)	(0.0009)	(0.0009)	(0.0009)	(0.0009)
CC			−0.0298		
			(0.0696)		
GC				0.1080	
				(0.1600)	
FC					0.3700**
					(0.1550)
lnpgdp	0.7710***	0.2550	0.5610***	0.6650***	0.6650***
	(0.1090)	(0.2780)	(0.0963)	(0.0891)	(0.0891)
lnso2	0.4330***	0.1390	0.3650***	0.3990***	0.39900***
	(0.0590)	(0.1250)	(0.0573)	(0.0529)	(0.0529)
lnsewage	0.4090***	0.3510***	0.4590***	0.4630***	0.4630***
	(0.0646)	(0.0715)	(0.0584)	(0.0539)	(0.0539)
lnnub	−0.4000*	0.0627	−0.1190	−0.3510*	−0.3510*
	(0.2280)	(0.3490)	(0.2110)	(0.1930)	(0.1930)
old	0.0030	−0.0085	−0.0035	0.0004	0.0004
	(0.0086)	(0.0071)	(0.0083)	(0.0076)	(0.0076)
edu	0.0006	0.0141	0.1060*	0.0172	0.0172
	(0.0556)	(0.0501)	(0.0605)	(0.0497)	(0.0497)
term	−0.0741***	0.0384**	0.0428**	0.0535***	0.0535***
	(0.0191)	(0.0181)	(0.0218)	(0.0158)	(0.0158)
Constant	−0.7790	4.9060**	0.3420	−0.3310	−0.3310
	(0.8310)	(2.3700)	(0.8090)	(0.7470)	(0.7470)
Provinces FE	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES
Observations	341	392	424	424	424
R-squared	0.750	0.426	0.682	0.737	0.737

Notes: ***, **, and * represent significant at 1, 5, and 10% significance level, respectively; standard errors are provided in parentheses.

affected government green investments (Zhang et al., 2021). Therefore, I use two dummy variables, *GC* and *FC*, to assess and control for the potential impact of the financial crisis and the green credit policy. *GC* measures the green credit policy, which I set at 1 for 2012 after the policy was announced and 0 for the years prior to 2012. *FC* measures the financial crisis, which is 1 for the year of 2008 and 0 for other years. The results are reported in Columns 4) and 5) of Table 3, where it can be seen that there is a significant positive effect of collectivism culture on green investments in the province, even after controlling for the financial crisis and green credit policy.

4.4 Heterogeneity issues

4.4.1 Heterogeneity analysis of governors' characteristics

Each governor has their own characteristics. Even with the same cultural background, governors with different personalities may have significantly different attitudes and practices when confronted with environmental issues (Yu et al., 2019). Local cadres are diverse, and their behaviour may differ significantly (Pizer and Yates, 2015). It is therefore important to explore the influence of the personal characteristics of governors.

TABLE 4 Heterogeneity analysis of governors' characteristics.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	lnGI	lnGI	lnGI	lnGI	lnGI	lnGI
Rice	−0.0004 (0.0036)	0.0042*** (0.0012)	−0.0007 (0.0020)	0.0033*** (0.0011)	0.0034 (0.0033)	0.0037*** (0.0011)
lnpgdp	−0.0705 (0.7340)	1.0000** (0.3860)	0.6920** (0.2640)	0.5680*** (0.1230)	0.5280 (0.3890)	0.5720*** (0.1050)
lnso2	0.8010** (0.3650)	0.3140** (0.1480)	0.3550** (0.1670)	0.1650** (0.0700)	0.7270*** (0.2070)	0.3840*** (0.0669)
lnsewage	0.5720*** (0.1610)	0.3010*** (0.0907)	0.5510*** (0.1520)	0.4760*** (0.0680)	0.3810*** (0.1280)	0.4440*** (0.0761)
lnnub	0.4480 (0.8350)	−0.8430* (0.4470)	−0.3800 (0.4230)	−0.4070 (0.2880)	0.3360 (0.8220)	0.0580 (0.2280)
old	−0.0195 (0.0200)	−0.0235 (0.0166)	−0.0297 (0.0223)	−0.0080 (0.0095)	−0.0200 (0.0182)	0.0044 (0.0096)
edu	0.0793 (0.1100)	0.0563 (0.0682)	0.231 (0.664)	−0.0025 (0.1100)	0.1160 (0.1410)	0.0991 (0.0788)
term	−0.0069 (0.0465)	−0.0663** (0.0259)	0.0317 (0.0703)	−0.0381 (0.0244)	−0.2140 (0.2940)	−0.0109 (0.0315)
Constant	−7.3950 (4.9530)	1.1050 (4.7490)	0.4480 (2.1550)	2.4590** (1.1020)	0.0034 (2.1680)	0.0037*** (0.9370)
Provinces FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Observations	127	297	121	303	70	354
R-squared	0.612	0.435	0.793	0.560	0.892	0.698

Notes: ***, **, and * represent significant at 1, 5, and 10% significance level, respectively; standard errors are provided in parentheses.

First, I separate the sample at age 57 to get younger group and older group. As presented in Column 2) of Table 4, the results for older governors (year>57) are significantly positive at the 1% level, while they are not significant among younger governors (year≤57) shown in Column 1) of Table 4. These results show that the positive effect of collectivism culture on green investment is more pronounced when governors are older than 57 years. The behavior of politicians often reflects their goals and aspirations to maximize personal utility, consolidate power, or achieve political promotion rather than social welfare (Lindbeck, 1976; Olson, 1993; Shleifer and Vishny, 1994; La Porta et al., 2002; Rajan and Zingales, 2003; Piotroski and Zhang, 2014). In China, governors have primary responsibility for the economic development and environmental governance. In an implicit rule, when local cadres are replaced, they are able to serve one term at the age of 57, but have to retire at the age of 58 (Zhang, 2011; Iversen and Palmer-Jones, 2015). Therefore, the political aspiration of local cadres declines sharply over age 57, and they shift their focus from environment governance to economic development. Moreover, Yu et al. (2019) present that there is a

positive linear relationship between governors' age and environmental efficiency. Because older governors may have more experience in pollution control, which favors environmental efficiency.

Second, I divided governors into those with a higher level of education (postgraduate and above) and those with a lower level of education (undergraduate and below). As presented in Column 4) of Table 4, the results for better educated governors are significantly positive at the 1% level, while they are not significant among governors that are not as well educated shown in Column 3) of Table 4. The results indicate that the higher the education level of the governor, the more significant the positive impact of collectivism culture on green investments. The education level of an official is closely related to their governing characteristics. In general, the higher the level of education, the greater the likelihood of an official being promoted. As a result, officials are likely to improve public satisfaction by enhancing environmental governance (Chen et al., 2017). Highly educated mayors are more confident to undertake environmental governance actions and are likely to use efficient

TABLE 5 Heterogeneity analysis of regional characteristics.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	lnGI	lnGI	lnGI	lnGI	lnGI	lnGI
Rice	0.0017 (0.0013)	0.0035** (0.0014)	0.0019 (0.0011)	0.0040** (0.0016)	0.0017 (0.0012)	0.0058*** (0.0015)
lnpgdp	0.4620*** (0.1170)	0.8240*** (0.1410)	0.3480*** (0.4230)	0.8460*** (0.1790)	0.5980*** (0.1300)	0.6350*** (0.1530)
lnso2	0.3070*** (0.0721)	0.5440*** (0.0844)	0.3440*** (0.0883)	0.4410*** (0.0925)	0.3400*** (0.0854)	0.3840*** (0.0848)
lnsewage	0.6340*** (0.0717)	0.2510*** (0.0876)	0.4680*** (0.0753)	0.3640*** (0.1080)	0.4350*** (0.0863)	0.4160*** (0.0881)
lnnub	-0.0175 (0.2810)	-0.5420* (0.2880)	-0.0226 (0.2680)	-0.1990 (0.3690)	-0.5000 (0.3070)	-0.0667 (0.3160)
old	-0.0015 (0.0089)	-0.0020 (0.0144)	-0.0155* (0.00926)	0.0228 (0.0170)	-0.0207* (0.0105)	0.0219 (0.0137)
edu	0.0223 (0.0654)	0.0244 (0.0827)	0.0388 (0.0665)	0.2510* (0.1320)	0.1480* (0.0764)	0.1140 (0.1020)
term	0.0601*** (0.0201)	-0.0411 (0.0258)	0.0817*** (0.0268)	-0.0153 (0.0453)	-0.0134 (0.0351)	-0.0782** (0.0323)
Constant	-0.8660 (0.9690)	0.4640 (1.3180)	3.0140*** (0.9870)	-3.4190** (1.5020)	2.7510** (1.1020)	-1.7190 (1.3210)
Provinces FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Observations	206	215	250	174	225	199
R-squared	0.788	0.723	0.638	0.763	0.676	0.725

Notes: ***, **, and * represent significant at 1, 5, and 10% significance level, respectively; standard errors are provided in parentheses.

environmental governance techniques to improve environmental efficiency. In addition, highly educated officials are concerned about the negative impact of extensive economic growth on environmental pollution, and they put more emphasis on sustainable economic development (Yu et al., 2019).

Studies in South Africa and Latin America have confirmed the above results. For example, Besley et al. (2012) found that highly educated leaders in South Africa were able to allocate regional resources and reduce local carbon emissions by developing rigorous and effective environmental policies. Gibson and Lehoucq (2003) determined that Guatemalan mayors with advanced degrees performed well in environmental governance, for example by employing more technical staff to manage forest security.

Finally, I analysed the effect of heterogeneity in governors' tenure. As shown in Column 6) of Table 4, the results are significantly positive at the 1% level when governors' tenure is longer and are not significant when the tenure is shorter presented in Column 5) of Table 4. This indicates that the longer a governor's term of office, the more significant the positive impact

of collectivism culture on green investments. Officials with shorter terms of office tend to try and increase economic growth at the expense of the environment during their tenure to gain a competitive advantage in seizing promotion opportunities. If the tenure of officials is too long, they are less likely to be promoted, which means that their enthusiasm for economic development will diminish and their attention to the environment will increase (Yu et al., 2019).

4.4.2 Analysis of the heterogeneity of regional characteristics

In the long run, environmental regulation and economic development are consistent (Niu et al., 2022). I first examined the effect of provincial characteristics. In Columns 1) and 2) of Table 5, I measure the environmental status of each province in terms of its average PM2.5 concentration. The coefficient of collectivism is significant at the 5% level when the province has a poor environment. The results indicate that the more polluted the province, the more significant the positive impact of collectivism culture on green investments. Environmental degradation hinders

further economic development, and the government recognises the need to change the traditional approach of driving economic growth at the expense of the environment (Zhang, 2007). In provinces with high levels of environmental pollution, governors are more willing to make green investments to improve the environment.

Culture profoundly influences personal norms and values during childhood (Triandis, 2001). However, a person is not only influenced by the culture of their hometown, but also adapts to the culture in which they live and work. As reported in Column 4) of Table 5, a leader who serves in a province with a strong collectivism culture prefers to make more green investments. Because they are further supported by their environment. Thus, it has a positive impact on green investments. While a leader who serves in a province with a strong individualist culture is inhibited by it, which is shown in Column 3) of Table 5.

Finally, provinces with above-average marketability indices are defined as developed market regions and those with below-average levels as less developed market regions, according to the *China Provincial Marketability Index Report*. The results in Columns 5) and 6) of Table 5 reveal that the influence of collectivism culture on green investment is more pronounced in developed market areas. Such areas have higher economic and living standards than less developed market areas, and governors are more willing to respond to the call for green development when there is less economic pressure. In addition, higher living standards make the public more concerned about environmental issues, and governors are willing to respond to the public's appeal. In contrast, the economic conditions in less developed market areas are worse in comparison, and in some areas, there is even a shortage of food. Allocating resources to improving the environment in these areas will inevitably affect economic development and thus the governor's green investments are limited.

5 Conclusion

With growing concerns worldwide on global warming, emissions reduction has become a major challenge for many countries. Countries are focusing on creating efficient energy systems to move towards a low-carbon economy. In this context, the role of investment in promoting and controlling carbon emissions is particularly important. Using panel data from 2004–2017 on 31 Chinese provinces, this study examines the relationship between the collectivism culture and green transition. The results indicate that 1) places with a stronger collectivism culture tend to make more green investments, 2) the results remain valid after a battery of robustness tests, 3) the positive effects of collectivism culture on green investments are more pronounced if the province governor is advanced in age, well educated, and holds a long tenure, and 4) such effects are more conspicuous in those provinces with more serious pollution, greater levels of collectivism, and more developed markets.

This study is relevant both theoretically and pragmatically. First, it promotes the government's implementation of green economic development. Driving green and low-carbon socioeconomic development is a key link to achieving high-quality growth. The government's supportive policies regarding the environment and resources are oriented towards the green transformation of social development as a whole. Therefore, studying governors' collectivism culture for the purpose of promoting environmental sustainability

through green investments could help the government better play its role and could therefore be useful in China's green, environmentally friendly, and sustainable development. Second, the government's development of green and low-carbon industries and the high-quality development of a green economy cannot be achieved without theoretical support. In this sense, this study fills a theoretical gap in the field of research on green investments from a cultural perspective. Therefore, this study has important implications for promoting green development and achieve carbon peaking and neutrality. Third, this study expands the possibility of rice theory application. My use of the theory to measure collectivism could provide some insight into how to broaden the scope of applying a classical theory to solve practical problems.

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

DQ: conceptualization, methodology, data curation, formal analysis, software, writing-original draft, writing-review and editing. I have read and agreed to the published version of the manuscript.

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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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Appendix A: Descriptive statistics

Variables	Obs	Mean	SD	Min	Median	Max
lnGI	429	11.667	1.217	4.859	11.830	14.164
Rice	434	36.285	33.430	0.209	22.252	89.684
lnpgdp	434	10.289	0.678	8.370	10.389	11.768
lnso2	434	3.757	1.300	−2.303	4.041	5.300
lnsewage	427	10.519	1.083	6.564	10.634	12.568
lnnub	434	3.903	0.301	2.294	3.912	4.557
old	434	58.094	4.242	36.000	59.000	65.000
edu	434	1.850	0.692	0.000	2.000	3.000
term	434	4.429	1.962	1.000	4.000	9.000

Considering that several of the variables are too large in magnitude, the variables (GI, pgdp, so2, sewage, and nub) are taken in logarithms.



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The coupling relationship between tourism economy and air quality in China: A province-level analysis

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Introduction: The development of tourism economy depends on air quality to a large extent, and good air quality is conducive to promoting the development of tourism economy. And it is crucial to understand the coupled and coordinated relationship between them. However, few studies have explored the coupling relationship between tourism and air quality. Therefore, it is necessary to further study the coupling relationship between tourism and air quality.

Methods: In this study, an index system was constructed to evaluate the development status of tourism economy and air quality system, and the entropy value method was used to weight the indexes. Using panel data of Chinese provinces from 2014 to 2020, a coupled coordination model was established, focusing on the degree of coordination between tourism economy and air quality.

Results: The empirical results show that during the sample period, China's tourism economic index is decreasing, and the regional development is unbalanced, showing the gradient of eastern region > central region > western region. The air quality index, on the other hand, fluctuates and increases, showing a spatial distribution pattern of "weekly high, high and low" of western region > eastern region > central region. The coupling coordination level of both regions shows an increasing trend, with the eastern region having the highest coupling coordination level and always in the stage of barely balanced development; the central region has the second highest coupling coordination level and the coupling coordination level is steadily increasing; the western region has the worst coupling coordination level and the coupling system tends to decline. The main type of coupling coordination effect is tourism economy lagged type, and the overall performance shows that the ambient air quality condition is better than the tourism economy development.

Discussion: This study clearly reveals the evolution, degree and types of coupling coordination in the tourism economy and air quality of the two systems, which contributes to the understanding of coupling and synergy of industrial development and ecological environment. This research also expands the application field of the CCDM model, and has a certain methodology contribution for further exploring the synergy and symbiosis mechanism of tourism economy development and environmental change.

KEYWORDS

tourism economy, air quality, entropy method, coupling coordination degree model, index system

1 Introduction

In many developing countries, tourism plays an important role in socio-economic development (Dogru and Bulut, 2018). Since the reform and opening-up in China, the tourism economy has grown at a high speed. In 2019, China achieved a total tourism income of 6.63 trillion yuan, and its comprehensive contribution rate to the national economy has reached 11.05% (China Tourism Research Institute), ranking the fastest developing country in the world in domestic tourism. The improvement of tourism economic development has undoubtedly promoted the rapid accumulation of material wealth and the promotion of people's livelihood and wellbeing in China in a short period of time. However, the development of tourism is often a double-edged sword. Large-scale tourist activities and the operation of tourism assistance and supporting facilities have brought serious ecological and environmental problems, among which the air pollution with the strongest public perception has aroused people's great concern (Zhang F. et al., 2022). Air pollution not only seriously endangers public health and life (Holgate, 2017; Martinez et al., 2018), but also has a negative effect on tourism travel, becoming an important factor hindering the high-quality development of tourism (Chen, 2017). Therefore, it is necessary to realize the coordination between the two subsystems of tourism economy and air quality, promote the rapid development of tourism in a sustainable way, and maintain good air quality at the same time.

In recent years, more and more scholars began to pay attention to the relationship between tourism and air quality. Most studies take carbon dioxide emissions as the representative variable of air quality to examine the impact of tourism on air quality. Most scholars come to the same conclusion that tourism will worsen air quality (Becken and Patterson, 2006; Lee and Brahmastre, 2013; Tiwari et al., 2013; Katircioglu et al., 2014; Ozturk, 2015; Zhang and Gao, 2016; Ahmad et al., 2018; Wang and Wang, 2018). A large amount of greenhouse gases are emitted by tourism through transportation, accommodation and other tourism activities, resulting in serious air pollution problems. Some scholars also believe that the relationship between tourism and carbon dioxide may vary depending on the level of national economic development and the strategies adopted for tourism development (Paramati et al., 2017). However, compared with other pollutants, CO₂ has negligible impact on air quality and human health, and is not a key pollutant (Robaina et al., 2020). Therefore, some scholars began to use PM₁₀, PM_{2.5}, O₃ and other variables to discuss the impact of tourism on air quality (Keiser et al., 2018; Liu et al., 2019a; Eusebio et al., 2020; Zeng et al., 2021). For example, Saenz-de-Miera and Rosselló (2014) shows that when the number of tourists increases by 1%, the PM₁₀ concentration level will increase by 0.45%.

While tourism brings air pollution, it will also be affected by air pollution. Good air quality is considered as one of the main attractions of tourist destinations (Goh, 2012; Becken and Wilson, 2013), which is crucial to the competitiveness of tourist destinations (Gao and Kerstetter, 2016). But when the air is polluted, it will hinder the development of tourism (Zhu, 2022). In some developed countries, the impact of air pollution index (CO₂ emissions) on international tourism is significantly negative (Nademi and Najibi, 2011). The Fukushima nuclear accident in Japan in 2011 greatly affected the inbound tourism of the whole country. Zhang X. et al. (2022) showed

that air pollution intensifies by 1%, the number of inbound tourists decreases by 1.171%. Outbound tourism will increase with the deterioration of air quality in origin (Wang et al., 2018). Dai et al. (2017) shows that seeking fresh air has become an important factor to promote China's outbound tourism. Xu et al. (2019) further explore which pollutants (PM_{2.5}, PM₁₀, SO₂ and NO₂) have the greatest negative impact on tourism activities in China.

With the rapid development of tourism industry in the world, the relationship between tourism industry and the environment has become increasingly prominent. The concept of coupling originates from physics, and refers to the dynamic relationship between two or more complex systems through the interaction of subsystems or elements (Tang, 2015). As one of the methods to measure the interaction effect, it is widely used in environmental research. Previous studies have done empirical research on the coupling and coordination relationship between tourism and environment in Beijing (Li and Weng, 2016), Qinghai (Xue, 2018), Shanxi (Liu et al., 2019b), Nagasaki (Liu and Suk, 2021) and other places. These studies reveal the interaction between tourism subsystem and environment subsystem, and show that the coordinated development of the two subsystems is crucial to the sustainable development of regional tourism. As an¹ important part of environmental quality, air quality has a complex interaction with tourism. However, few studies have explored the coupling relationship between tourism and air quality. Therefore, it is necessary to further study the coupling relationship between tourism and air quality.

In view of this, this study is based on the panel data of 31 provinces in China from 2014 to 2020. Firstly, it attempts to construct a coupling and coordination analysis framework of tourism economy and air quality. Secondly, the entropy method is used to obtain the index weight objectively. Finally, the coupling coordination degree model (CCDM) is used to comprehensively measure the coupling coordination degree between tourism economy and air quality. The purpose of this study is: 1) to reveal the dynamic trend of the coupled development of tourism economy and air quality; 2) Provide reference for the coordinated development of tourism economy and air quality in the process of macro-policy making. In addition, the coupling coordination degree between tourism economy and air quality proposed in this paper is an important reference for evaluating the environmental impact of tourism economic development. It provides an expanded perspective and a specific quantitative analysis tool for exploring in depth the ecological and environmental effects of tourism economic development. This method can be extended to explore the relationship between tourism economy and air quality in other regions at different levels. Theoretically, the analysis and the method also contribute to extending the understanding of coupling and synergy of industrial development and ecological environment.

The remainder of the article is structured as follows. Section 2 presents the materials and methods. Section 3 reports and discusses the empirical results. Finally, Section 4 is devoted to conclusions and

¹ China Tourism Research Institute. In 2019, China's total tourism revenue reached 6.63 trillion yuan, and the comprehensive contribution of tourism accounted for 11.05% of GDP [EB-OL]. <http://shareapp.cyol.com/cmsfile/News/202003/11/347732.html>.

TABLE 1 Index system used for evaluation of the relationship between tourism economy and air quality and the index weights.

Subsystem	First-class index	Second-class index	Index type	Entropy weight
Tourism Economy(<i>x</i>)	Tourism benefits	Total tourism incomes (100 million yuan) x_1	+	0.0605
		Foreign exchange earnings from international tourism (USD 10,000) x_2	+	0.1765
		Earnings from domestic tourism (100 million yuan) x_3	+	0.0603
		Proportion of total earnings from tourism in tertiary industry income (%) x_4	+	0.0416
		Proportion of total earnings from tourism in GDP (%) x_5	+	0.0431
	Tourism scale	Total number of tourists(10,000person-times) x_6	+	0.0583
		Number of international tourists (10,000person-times) x_7	+	0.1684
		Number of domestic tourists (10,000person-times) x_8	+	0.0586
		Proportion of tourism employees in tertiary industry employees (%) x_9	+	0.1751
		Total travel agencies (number) x_{10}	+	0.0559
		Total star-rated hotels (number) x_{11}	+	0.0465
		A-level scenic spots (number) x_{12}	+	0.0550
Air Quality(<i>y</i>)	air contaminants	Average concentrations of PM _{2.5} (ug/m ³) y_1	-	0.0846
		Average concentrations of PM ₁₀ (ug/m ³) y_2	-	0.0880
		Average concentrations of SO ₂ (ug/m ³) y_3	-	0.1066
		Average concentrations of CO(mg/m ³) y_4	-	0.1222
		Average concentrations of NO ₂ (ug/m ³) y_5	-	0.3173
		Average concentrations of O ₃ (ug/m ³) y_6	-	0.2813

recommendations, along with some limitations of the study and future research directions.

2 Materials and methods

2.1 Index system

There is a complex interaction between tourism and air quality. Scholars generally believe that on the one hand, the capital accumulation effect formed by the development of tourism economy can provide financial support for the improvement of air quality, on the other hand, the operation of tourism departments will consume a lot of energy and emit waste gas, causing serious environmental air pollution. High-quality ambient air quality provides strong support for tourism services. While attracting tourists, it can also increase the tourist experience of tourists and bring good economic benefits to tourism development. However, serious air pollution will have negative effects on tourism and hinder the development of tourism economy (Robaina et al., 2020; Zhang F. et al., 2022). Objectively, there are various contradictions and interactions between tourism economy and air quality. Therefore, the system composed of tourism economy subsystem and air quality subsystem is defined as a coupling system, and its coupling and coordination relationship plays an important role in the sustainable development of tourism and pollution control. According to the

conceptual framework and connotation of the coupling system, this paper constructs a comprehensive evaluation index system to measure the interaction between tourism economy and air quality. Refer to previous studies (Tang, 2015; Zheng et al., 2016; Liao K. C. et al., 2018; Wang et al., 2019; Geng et al., 2020; Geng et al., 2021), A comprehensive index system composed of two subsystems, three dimensions and 18 indicators was finally established (Table 1) based on the correlation analysis and significance test.

In the tourism economic subsystem, the dimension of tourism benefits represents the status of tourism, including total tourism incomes, foreign exchange earnings from international tourism, earnings from domestic tourism, proportion of total earnings from tourism in tertiary industry income, and proportion of total earnings from tourism in GDP. The three indicators of total tourism income, foreign exchange earnings from international tourism and earnings from domestic tourism indicate the direct economic income obtained by tourism. The proportion of total earnings from tourism in tertiary industry income, and the proportion of total earnings from tourism in GDP reflect the status of tourism in the tertiary industry and the national economy. The dimension of tourism scale shows that the overall scale of tourism, including the total number of tourists, number of international tourists, number of domestic tourists, the Proportion of tourism employees in tertiary industry employees, total travel agencies, total star-rated hotels and A-level scenic spots. The three indicators of the total number of tourists, number of international tourists, number of domestic

tourists indicate the scale of the tourism market. The Proportion of tourism employees in tertiary industry employees indicates the scale of tourism employment. The number of travel agencies, the number of star-rated hotels and the number of A-level scenic spots indicate the scale of tourism enterprises.

In the air quality subsystem, at present, the air quality index (AQI) formulated by the Ministry of Ecology and Environment is mainly used in China to describe the air quality, and its evaluation index system includes six air pollutant indexes: SO₂, NO₂, PM₁₀, CO, O₃ and PM_{2.5}. This index system is also used in this study. Due to the strong diffusion of air pollution, this study measured the air quality of provincial capital cities based on the annual average data of pollution indicators, and represented the overall air quality of the province.

2.2 Data collection and pre-processing

Limited by the lack of data in Hongkong, Macau and Taiwan Province all the year round, it is not included in the scope of this study. Finally, 31 provincial units in China are selected as research samples. The air quality data is collected on the China Air Quality Online Monitoring and Analysis Platform (<https://www.aqistudy.cn/historydata/>). Tourism economic data comes from the Statistical Yearbook of China and the Statistical Yearbook of China Tourism in the corresponding years, and statistical bulletins of national economic and social development of various provinces. As for the research period, since the Air Quality Standard (GB3095-2012) has been gradually implemented since 2013, it is limited to the availability and authority of data, so 2014–2020 is chosen as the research period.

In order to eliminate the influence of dimensions, it is necessary to standardize the original data by using formulas (1) and (2). For a positive index (Liao K. C. et al., 2018), namely:

$$X'_{ij} = \frac{X_{ij} - \min_{1 \leq j \leq n} X_{ij}}{\max_{1 \leq j \leq n} X_{ij} - \min_{1 \leq j \leq n} X_{ij}} \quad (1)$$

For negative exponents, namely:

$$X'_{ij} = \frac{\max_{1 \leq j \leq n} X_{ij} - X_{ij}}{\max_{1 \leq j \leq n} X_{ij} - \min_{1 \leq j \leq n} X_{ij}} \quad (2)$$

Where, X'_{ij} and X_{ij} are the standard value and original value of index j in the i year, respectively; $\max_{1 \leq j \leq n} X_{ij}$ and $\min_{1 \leq j \leq n} X_{ij}$ represent the maximum and minimum values of index j in all years, respectively.

2.3 Evaluation of the indicators' weight

In this study, the entropy weight method is used to determine the index weight (Wang et al., 2019). As an objective assignment method, the entropy weight method can avoid the subjectivity in the calculation process and is widely used in empirical research. The calculation steps are as follows:

Calculate the proportion of indicators:

$$R_{ij} = \frac{X'_{ij}}{\sum_{i=1}^m X'_i} \quad (3)$$

Calculate the index information entropy:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^m R_{ij} \times \ln R_{ij} \quad (0 \leq e_j \leq 1) \quad (4)$$

Calculate index entropy redundancy:

$$d_j = 1 - e_j \quad (5)$$

Calculate index weight:

$$w_j = \frac{d_j}{\sum_{j=1}^n d_j} \quad (6)$$

2.4 Evaluation of tourism economy and air quality

Based on the entropy method to determine the index weight, the comprehensive evaluation model is used to obtain the comprehensive development level of the two subsystems of tourism economy and ambient air quality (Zheng et al., 2016). Assuming that $x_1, x_2, \dots, x_m$ represents the index of tourism economy subsystem, and $y_1, y_2, \dots, y_n$ represents the index of air quality subsystem, then:

$$f(x) = \sum_{i=1}^m a_i \times x'_i \quad (7)$$

$$g(y) = \sum_{i=1}^n b_i \times y'_i \quad (8)$$

Where $f(x)$ represents the comprehensive index of tourism economy; $g(y)$ represents the comprehensive index of air quality; x'_i and y'_i are the values of tourism economy and air quality after standardized treatment respectively; a_i and b_i respectively represent the weight of each index in tourism economy and air quality subsystems.

2.5 The coupling coordination degree model

As an effective tool to identify the multi-coupling relationship between different systems, the coupling coordination model is widely used in the fields of economy, ecology, transportation and tourism (Tang, 2015). In this paper, a coupling coordination model of tourism economy and air quality (CCDM) is constructed. The calculation steps of this model are as follows:

$$C = \left\{ \frac{f(x) \times g(y)}{\left[\frac{f(x) + g(y)}{2} \right]^2} \right\}^{\frac{1}{2}} \quad (9)$$

$$T = \alpha f(x) + \beta g(y) \quad (10)$$

$$D = \sqrt{C \times T} \quad (11)$$

TABLE 2 Discriminating standard of coordinated coupling of tourism economy and air quality.

Classes	Coupling coordination degree	Subclasses	
Superiorly balanced development	$0.8 < D \leq 1$	Superiorly balanced development with tourism economy lagged	$g(y) - f(x) > 0.1$
		Superiorly balanced development with air quality lagged	$f(x) - g(y) > 0.1$
		Superiorly balanced development with tourism economy and air quality	$0 \leq f(x) - g(y) \leq 0.1$
Barely balanced development	$0.5 < D \leq 0.8$	Barely balanced Development with tourism economy lagged	$g(y) - f(x) > 0.1$
		Barely balanced Development with air quality lagged	$f(x) - g(y) > 0.1$
		Barely balanced Development with tourism economy and air quality	$0 \leq f(x) - g(y) \leq 0.1$
Slightly unbalanced development	$0.3 < D \leq 0.5$	Slightly unbalanced development with tourism economy lagged	$g(y) - f(x) > 0.1$
		Slightly unbalanced development with air quality lagged	$f(x) - g(y) > 0.1$
		Slightly unbalanced development with tourism economy and air quality	$0 \leq f(x) - g(y) \leq 0.1$
Seriously unbalanced development	$0 < D \leq 0.3$	Seriously unbalanced development with tourism economy lagged	$g(y) - f(x) > 0.1$
		Seriously unbalanced development with air quality lagged	$f(x) - g(y) > 0.1$
		Seriously unbalanced development with tourism economy and air quality	$0 \leq f(x) - g(y) \leq 0.1$

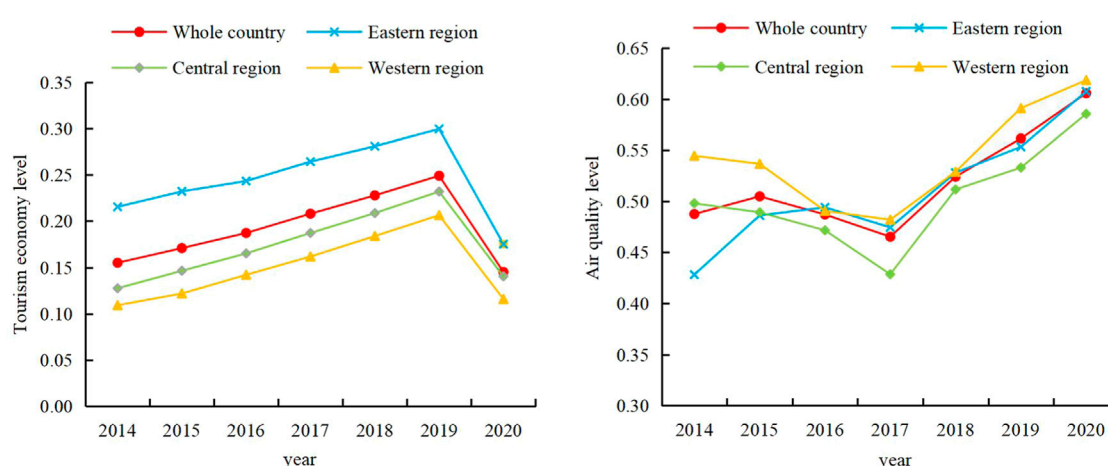


FIGURE 1

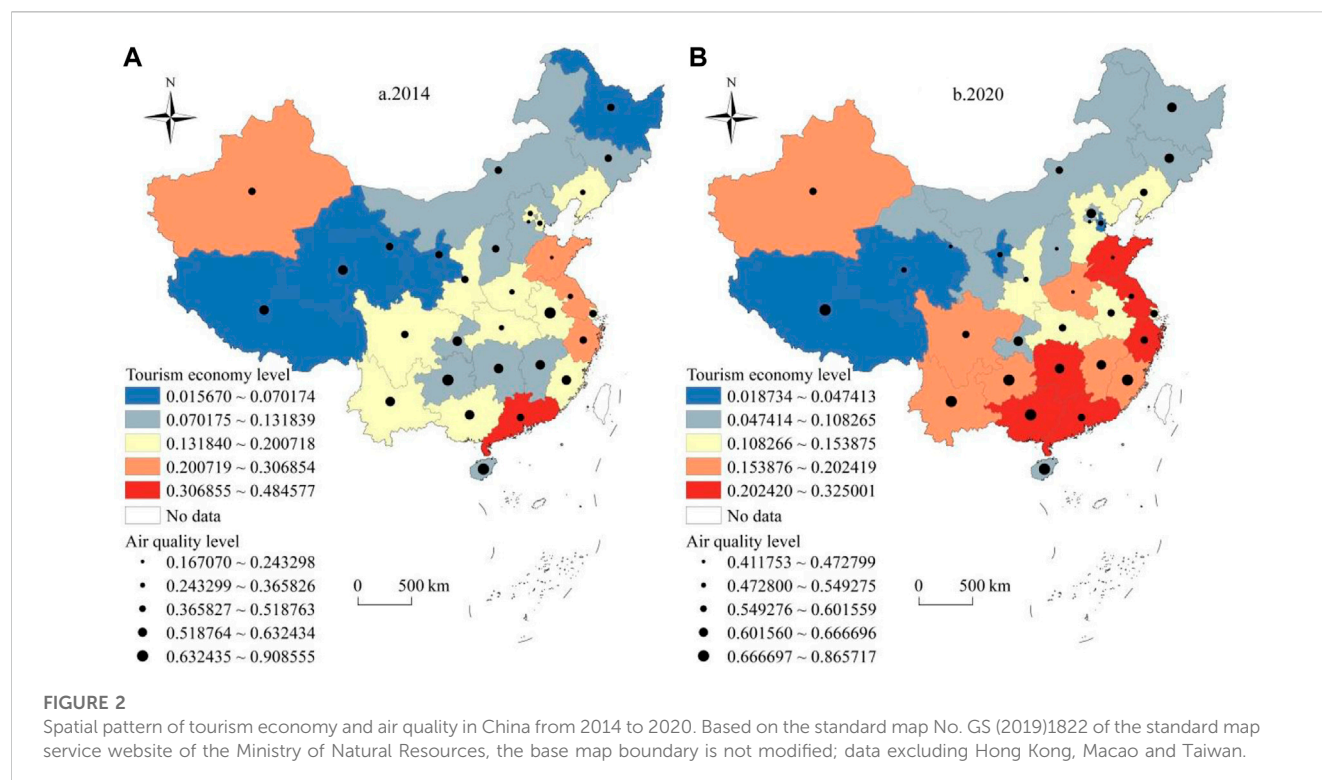
Trends of the comprehensive levels in subsystems.

Where $f(x)$ and $g(y)$ respectively represent the comprehensive index of tourism economy and air quality; C is the coupling degree, which measures the degree of interaction between subsystems; D is the coupling coordination degree, which measures the coordination degree of each subsystem in the development and evolution; T is the comprehensive coordination index; α and β are the undetermined weights of each subsystem. As tourism economy and air quality are equally important to regional development, they are both set to 0.5 by referring to the general treatment methods of previous studies (Tang, 2015). Referring to the research results of Li et al. (2012), the coupling and coordinated development types of tourism economy and air quality are divided into four classes and 12 subclasses, as shown in Table 2.

3 Results and discussion

3.1 Results of overall level of subsystems

Entropy method and comprehensive evaluation model were used to calculate the comprehensive development index of tourism economy and air quality of 31 provinces, autonomous regions and municipalities in China from 2014 to 2020, and ArcGIS 10.2 software was used to make spatial visualization of the measurement results of tourism economy and air quality from 2014 to 2020. In order to compare the differences among regions, 31 provinces, cities and autonomous regions are divided into three regions. They are the eastern region (Beijing, Tianjin, Hebei,



Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Guangxi and Hainan), the central region (Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei and Hunan) and the western region (Mongolia, Chongqing, Sichuan, Guizhou, Yunnan, Xizang, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang).

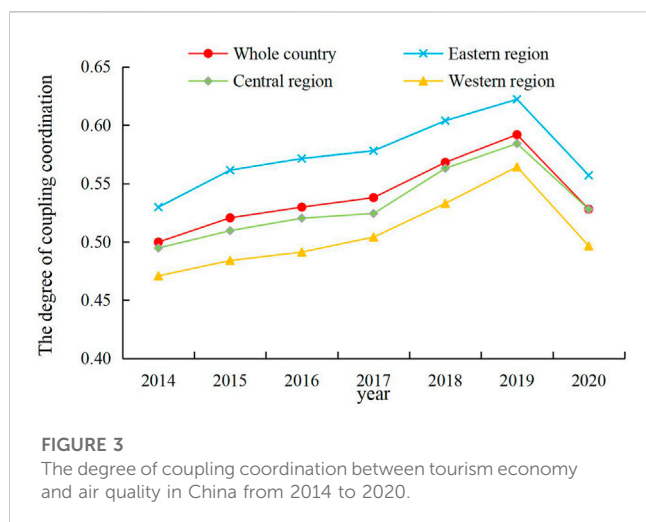
3.1.1 Results of overall level of tourism economic subsystem

As can be seen from Figure 1, during the study period, the tourism economic index of China showed a fluctuating downward trend, with its value dropping from 0.155 in 2014 to 0.145 in 2020, indicating that the overall level of tourism economic development has declined. At the same time, the development and evolution of tourism economy has obvious characteristics in stages, which can be divided into two stages according to its changing trend. 2014–2019 is a rapid rising period, with an average annual growth rate of 9.944%. During this period, China has promoted the overall level of tourism economy by continuously integrating regional tourism resources, improving regional supporting facilities, optimizing tourism policies and innovating tourism product formats. However, in 2020, novel coronavirus epidemic broke out and spread to all parts of the country, which caused a serious impact on the tourism economy. The rapidly advancing tourism industry was forced to press the pause button, and the tourism economic index plummeted from 0.249 in 2019 to 0.145 in 2020. From the perspective of the three regions, the annual average of the comprehensive index of tourism economy in the eastern region (0.244) is higher than that in the central region (0.172) and the western region (0.149), showing a gradient decreasing feature. The result is consistent with the actual situation of tourism development in China. From the perspective of

provinces, it can be seen from Figure 2A that the highest tourism economic index in 2014 was Guangdong (0.485), followed by Zhejiang, Shandong, Jiangsu, Xinjiang, Beijing, Liaoning and Shanghai. The high-level tourism economic index mainly distributed in the eastern coastal areas, and to some extent showed a spatial distribution pattern of decreasing from the eastern coastal areas to the northwest inland areas. Ningxia (0.016) has a low tourism economic index, followed by Tibet, Qinghai, Gansu and Heilongjiang. As can be seen from Figure 2B, in 2020, the tourism economic index of all provinces (cities, autonomous regions) will be below 0.4, and the tourism economic index of Guangdong will obviously drop, and Tianjin, Beijing, Liaoning, Zhejiang, Shanghai and other places will also drop. The high-value areas are still mainly concentrated in the eastern region, with the highest value being Guangdong (0.325), followed by Guangdong, Zhejiang, Shandong, Jiangsu, Guangxi, Hunan, Sichuan, Yunnan, Xinjiang, Jiangxi, Guizhou, Fujian and Henan. The tourism economic index of Ningxia (0.019) is still low, but the tourism economic index of Southwest China has generally improved, with Guizhou and Yunnan increasing the most. On the whole, from 2014 to 2020, the national tourism economic index dropped significantly, the regional differences among provinces gradually narrowed, and the spatial distribution gradually tended to be balanced.

3.1.2 Results of overall level of air quality subsystem

As can be seen from Figure 1, on the whole, the average air quality index of China during the sample period is 0.519, which is at a medium level, indicating that there is still much room for improvement of air quality. Its development trend has turned



into a fluctuating upward trend, with the air quality index rising from 0.487 in 2014 to 0.606 in 2020, with an average annual growth rate of 3.685%. According to the three regions, the air quality index in the western region is the highest (0.542) > that in the eastern region (0.510) > that in the central region (0.502), showing a spatial distribution pattern of “weekly, high, low”. From the perspective of provinces, it can be seen from Figure 2A that the highest air quality index in 2014 was distributed in Hainan (0.909), followed by Anhui, Guizhou, Tibet, Yunnan, Jiangxi and Qinghai. Provinces (cities, autonomous prefectures) with medium air quality index (0.365827–0.518763) have the most, and Shandong (0.167) has the lowest air quality index, followed by Hebei, Tianjin, Beijing, Liaoning, Hubei, Jiangsu and Henan, showing a spatial pattern with Beijing-Tianjin-Hebei urban agglomeration as the low-value core and increasing all around. As can be seen from Figure 2B, the number of high-value areas of air quality index increased obviously in 2020, mainly distributed in southwest and south China, with the highest value in Hainan (0.866), followed by Guizhou, Guangxi, Tibet, Yunnan, Fujian, Chongqing, Hunan, Jilin, Jiangxi, Heilongjiang and Beijing. The lowest value is distributed in Shanxi (0.412), followed by Gansu, Shandong, Hebei, Henan, Tianjin, Qinghai, Shaanxi, Ningxia and Jiangsu. On the whole, the coefficient of variation of air quality index showed a downward trend from 2014 to 2020, indicating that the regional differences among provinces decreased and the spatial distribution became more and more balanced.

3.2 Results of the degree of coupling coordination

3.2.1 Time evolution characteristics of coupling coordination

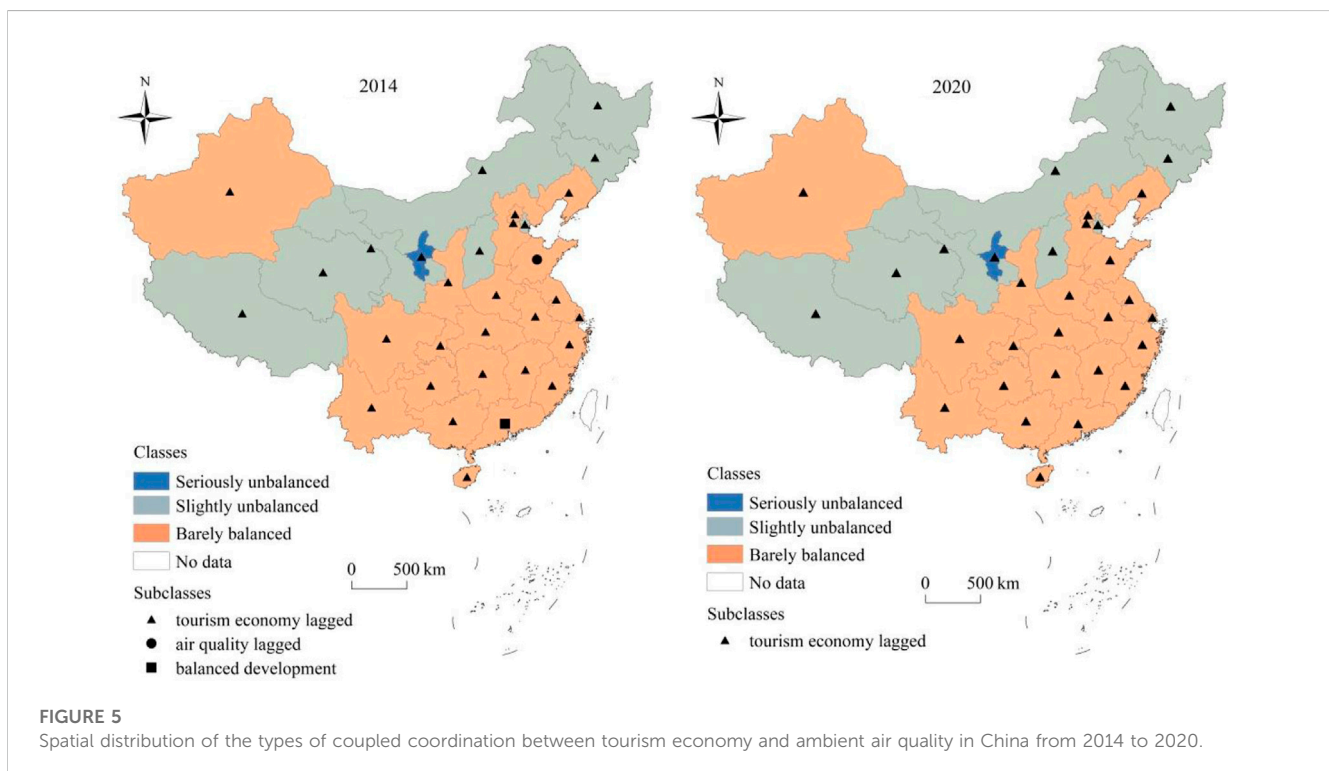
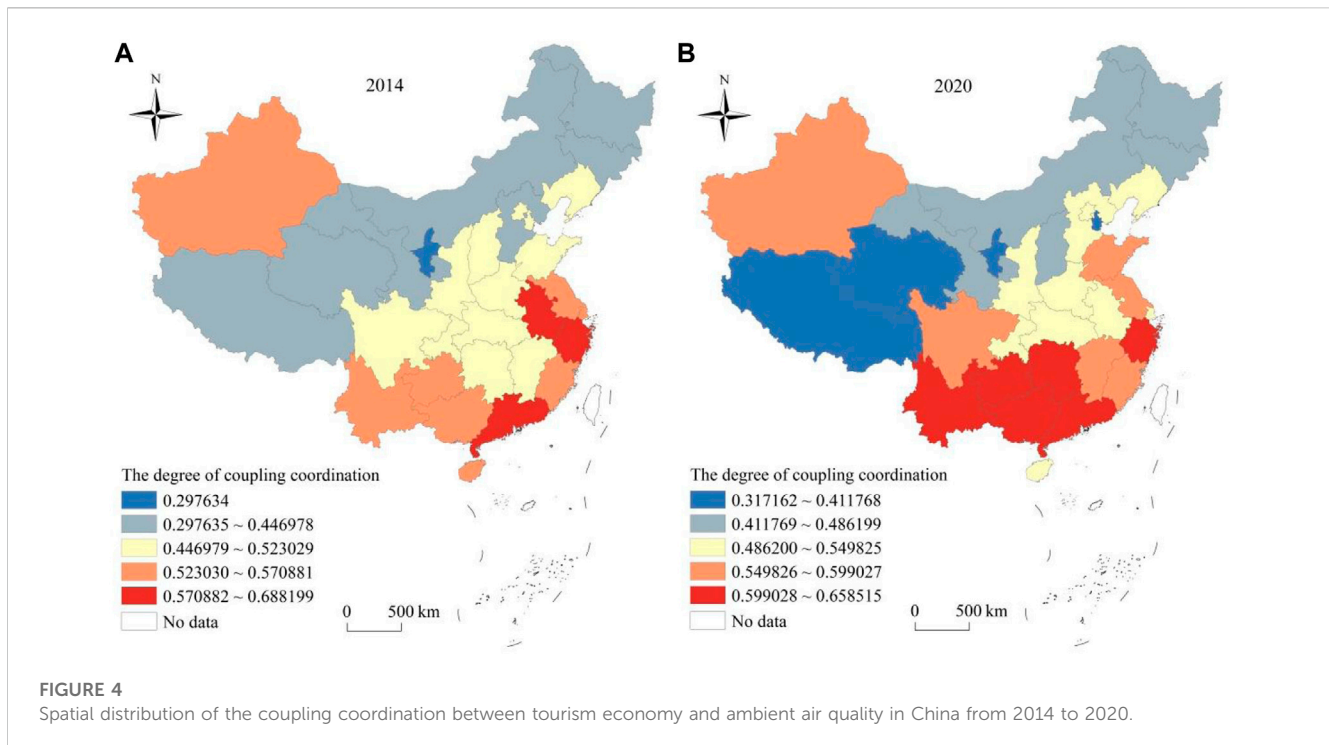
As can be seen from Figure 3, the coupling coordination degree of tourism economy and air quality in China is not high in the whole during the inspection period, with the value between 0.4 and 0.6, which is mainly in the stage of barely balanced development, and there is still a lot of room for optimization in the future. From the time series, the coupling coordination degree of tourism economy

and air quality in China showed a fluctuating growth trend during the study period, and the overall coordination level was improved. The value of coupling development index increased from 0.499 in 2014 to 0.528 in 2020, and the peak value appeared in 2019 (0.592), which indicated that the coupling coordination effect of tourism economy and air quality was getting better. From the overall stage evolution, before 2014, the coupling coordination degree of the two subsystems was less than 0.5, which belonged to the stage of slightly unbalanced development. In 2015, the coupling coordination degree was greater than 0.5, which entered the stage of barely balanced development. This may be related to the policy document of “Several Opinions of the State Council on Promoting the Reform and Development of Tourism Industry” (Guo Fa [2014] No.31) promulgated by the state, which helped the tourism industry to flourish, thus promoting the coupling state of tourism economy and ecological environment.

From the perspective of regional coupling coordination degree, the coupling coordination degree between tourism economy and air quality in the three major regions of China, east, central and west, is generally fluctuating and rising, and the eastern region fluctuates from 0.530 to 0.557, which is always in the stage of barely balanced development. The fluctuation of the central region increased from 0.495 to 0.528, and it experienced the evolution process from slightly unbalanced development (2014–2015) to barely balanced development (2015–2020), which indicated that the tourism economy and air quality in the central region had passed the running-in period and entered the basic coordination stage in the acceptable range of coupling coordination. The fluctuation of the western region increased from 0.471 to 0.497, which experienced the evolution process of slightly unbalanced development (2014–2016)-barely balanced development (2016–2019)-slightly unbalanced development (2019–2020), and the system tended to decline. The main reason was that the tourism industry in the western region was weak, which was hit hardest by the COVID-19 epidemic, and the tourism economic system declined.

3.2.2 Spatial pattern evolution of coupling coordination

From the spatial distribution of the coupling coordination degree (Figure 4), the spatial agglomeration of the coupling coordination degree of tourism economy and air quality in China was obvious in 2014, and the spatial distribution pattern decreased from the eastern coastal areas to the northwest inland areas. The high-value areas of coupling coordination degree were basically located in the coastal areas, and Guangdong had the highest coupling coordination degree, with only four high-value distribution points in the inland areas: Anhui, Yunnan, Guizhou and Xinjiang. The low-value areas of coupling degree are mainly distributed in the western region, and there is a “trough” phenomenon in Ningxia, with the lowest value of coupling degree. By 2020, the high-value coupling coordination areas will continue to extend to the central and western regions, and the number of high-value coupling coordination areas will increase, with an obvious trend of contiguous development. Guangdong (0.659) has the highest coupling coordination degree, followed by Guangxi, Hunan, Zhejiang, Yunnan, Guizhou, Jiangsu, Fujian, Sichuan, Jiangxi, Shandong and Xinjiang. Ningxia (0.317) has the lowest coupling coordination degree, followed by Qinghai, Tianjin,



Tibet, Gansu, Shanxi, Heilongjiang, Jilin and Inner Mongolia. On the whole, the coupling coordination degree of tourism economy and air quality in China is on the rise, but some areas have also dropped.

From the spatial evolution of coupling coordination types (Figure 5), there are three types of coupling coordination types between tourism economy and air quality in China in 2014, among which the number of barely balanced development types is the

largest, mainly concentrated in East China, South China and Southwest China, including 16 provinces such as Guangdong, Fujian, Shanghai, Jiangsu, Anhui and Jiangxi, accounting for 51.61% of the study sample. The provinces with slightly unbalanced development types are concentrated in Northeast China, North China and Northwest China, including 14 provinces such as Beijing, Tianjin, Hebei, Shandong and Inner Mongolia, accounting for 45.16% of the study samples. The province and city with Seriously unbalanced development is Ningxia, accounting for only 3.23% of the study sample. By 2020, the barely balanced development areas will go further north, with Beijing, Hebei, Liaoning, Henan and Hubei becoming the barely balanced development types, while the coupling coordination types of other provinces will remain unchanged. So far, the number of provinces with barely balanced development types is 22, accounting for 70.97% of the research samples. China's tourism economy and air quality have basically achieved relatively coordinated development, which shows that under the encouragement of national policies, the intensive and low-carbon development of tourism industry has been promoted, thus enhancing the air quality. Meanwhile, the improvement of air quality has provided material guarantee for the development of tourism, making the "tourism economy-air quality" composite system continuously evolve towards the direction of coordination and optimization. However, there is still much room for improvement, and the whole needs to evolve to the stage of superiorly balanced development.

Judging from the synchronization of the relative development of the system (Figure 5), the main type of coordination effect between tourism economy and air quality in China is tourism economy lagged. In 2014, except for Shandong's air quality lagged and Guangdong's system balanced development, all other provinces are tourism economy lagged. By 2020, all provinces show tourism economy lagged. It shows that at present, the improvement of the coupling coordination degree of the complex system of "tourism economy-air quality" in China mainly depends on strengthening the growth of tourism economy, and the driving effect of air quality improvement is slightly insufficient. Therefore, in the future, it is urgent to speed up the construction of tourism industry on the basis of protecting the existing air environment, and make up the shortcomings of tourism economy.

4 Conclusion and implications

4.1 Conclusion

This study takes the panel data of 31 provincial units in China from 2014 to 2020 as the research sample, and uses entropy method and comprehensive evaluation model to measure the comprehensive level of tourism economy and air quality. The coupling coordination degree model is used to comprehensively measure the coupling coordination degree between tourism economy and air quality. The main conclusions are as follows:

- (1) From the comprehensive development level of tourism economy and air quality, the tourism economic index shows a fluctuating downward trend, with its value dropping from

0.155 to 0.145. At the same time, the regional development is unbalanced, showing the gradient decreasing characteristics of the eastern region > the central region > the western region. The air quality index fluctuated from 0.487 in 2014 to 0.606 in 2020, showing a spatial distribution pattern of "weekly, high and low", that is, western region > eastern region > central region.

- (2) From the overall characteristics of the coupling coordination degree, the coupling coordination degree between China's tourism economy and air quality showed a fluctuating growth trend during the study period, and the overall coordination level was improved. The eastern region has the highest level of coupling coordination, and it is always in the stage of barely balanced development; The level of coupling coordination in the central region is the second, and it has roughly experienced the evolution process of slightly unbalanced development - barely balanced development; The coupling coordination level in the western region is the worst, and it has experienced the evolution process of slightly unbalanced development - barely balanced development - slightly unbalanced development, and the system tends to decline. The main type of coordination effect is tourism economy lagged, which indicates that air quality is better than the development of tourism economy.

4.2 Implications and future directions

Based on the above research conclusions, the following policy recommendations are put forward: 1) Pay attention to the development of tourism industry and change the *status quo* of lagging tourism economy. From the perspective of the three regions, the eastern region should speed up industrial adjustment and technological innovation, promote the modernization of tourism, and transfer some superior resources to the central and western regions. The central region should fully tap its own resource potential, strengthen the integration of tourism resources, and stimulate the vitality of tourism development. The western region should strengthen the construction of tourism infrastructure and public service system, actively learn from the advanced technology and experience of the eastern region, and optimize the return on tourism investment. At the same time, we should promote the optimization and upgrading of the tourism industry itself, further realize the efficient utilization of tourism resources, energy conservation and emission reduction, and realize the active integration of tourism development into air environmental protection. 2) In the post-COVID-19 era, the government should increase investment in environmental governance and encourage the use of clean energy to promote the green development of tourism (Wan et al., 2021; Kang et al., 2022; Liu H. Y. et al., 2022; Liu P. H. et al., 2022; Tao et al., 2022; Tian et al., 2022).

The relationship between tourism economy and air quality has become the focus of current research. However, most of the previous studies did not reflect the interaction between tourism and air quality. The coupling coordination degree model (CCDM) provides an effective method for evaluating the interaction between tourism economy and air quality. Existing research has conducted empirical research on the coupling and coordination relationship between tourism and the environment, such as Beijing,

Shaanxi and other cities (Li and Weng, 2016; Xue, 2018; Liu et al., 2019a). Air quality is an important part of environmental quality, and few studies have discussed the coupling relationship between tourism and air quality. According to the conceptual framework and connotation of coupling system, this paper constructs a comprehensive evaluation index system to help understand the interaction between tourism economy and air quality. In addition, the entropy method is an objective assignment method, which can avoid the defect of subjective weight determination. The combination of entropy method and coupling coordination model is an effective method, which is widely used in empirical research. Through comprehensive evaluation index system, entropy method and coupling coordination model, this paper reveals the dynamic trend of coupling development of tourism economy and air quality, which contributes to the understanding of coupling and synergy of industrial development and ecological environment. This research also expands the application field of the CCDM model, and has a certain methodology contribution for further exploring the synergy and symbiosis mechanism of tourism economy development and environmental change.

What needs to be explained is that the article has extensively absorbed the existing research results, tried to be scientific and reasonable, and tried to build an evaluation index system of tourism economy and air quality. However, both of them are complex systems involving various elements of human and land. At present, the academic circles have not formed a consistent and perfect research system, and some indicators still have room for improvement. In the future, a systematic and comprehensive index system should be further built. Due to the availability of data, this paper selects the provincial scale for research, and the air quality of provincial capital cities represents the overall air quality of the province. There may be some deviations in the calculated results, and the data of city and county scale can be further used for refined research in the future. In addition, due to the limitation of space, the article does not discuss the influencing factors of spatial correlation pattern of coupling coordination degree, and follow-up sustainable expansion research.

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Data availability statement

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

Author contributions

SZ performed the theory analysis and conceptualization and contributed to revising the manuscript. QL conducted the empirical analysis and drafting the paper. YK collected the data and improved the writing and conclusions. XC improved the manuscript and validation.

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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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Climate change, environmental regulations, and firms' efforts to reduce pollutant emissions

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Environmental regulation is an important tool for achieving environmental protection. This study investigated how climate change affects firms' actions to reduce pollutant emissions through environmental regulations. We conducted a pooled OLS regression analysis using data from Chinese industrial firms that were above the designated size from 2006 to 2013. The results showed that firms reduce SO₂ emissions in response to climate change, particularly when environmental regulations are more stringent. However, firms prefer to reduce productivity and implement "end-of-pipe" interventions than engage in more green innovation. Our findings highlight how firms deal with climate change under the pressure of environmental regulations and whether ecological considerations align or conflict with economic goals.

KEYWORDS

climate change, environmental regulation, pollutant emission, factor input of productivity process, end of pipe intervention, green innovation

1. Introduction

Climate change is a pressing global issue that threatens environmental conditions essential to human survival. In addition to causing rising sea levels and damaging ecological systems, climate change exacerbates environmental deterioration by increasing the likelihood of contaminants breaking down into harmful substances at higher temperatures. However, "going green" is difficult (Clarke et al., 1994). As the main sources of pollutant emissions, firms have little incentive to reduce pollution without regulations (Coase, 1960). Furthermore, reducing pollutant emissions may cause an economic lag that can limit productivity. The conflict between environmental concerns and economic growth is a complex issue that perplexes many developing countries.

Developing countries have sacrificed the environment for economic development resulting in many adverse repercussions for the global ecological system and public health (Ebenstein, 2012). To achieve sustainable development, developing countries must overcome the following challenges. First, there is insufficient incentive for firms to reduce pollutant emissions, which is due to the characteristics of the public goods environment and the externality of emissions. As a result, firms lack the motivation to actively reduce pollution without external regulations, which leads to public demand for regulations (Nordhaus, 2019).

Second, achieving a harmonious coexistence between economic growth and the environment is essential. In the process of economic growth, production demands resources and emits pollutants into the environment. Reducing pollutant emissions means accepting the loss of economic growth opportunities (Gray and Shadbegian, 2003).

Most existing studies suggest that climate change has a negative effect on firms' production processes and financial behavior, such as capital income (Dell et al., 2009), industry outputs (Hsiang et al., 2017), employees' mental and physical health (Ito and Zhang, 2020), and the overall economic system (Stern, 1995; Dell et al., 2012). Faced with climate change, firms tend to passively accept its consequences and bear the associated costs and damages (Clarkson et al., 2004). However, little is known about whether firms take responsibility for reducing pollutant emissions. China, as the world's largest developing country and emerging market, has achieved remarkable economic growth (Allen et al., 2005) while also serving as the world's industrial factory with the world's largest population. Consequently, it faces significant threats from climate change. However, China's success in environmental protection can be viewed as an exemplar of promoting green development worldwide (He et al., 2020).

In contrast to the market-oriented behavior in developed Western countries, political incentives encourage firms in China to trade-off public welfare. China has a land area of 9.6 million sq km, making it difficult for the central government to manage the country (Li and Zhou, 2005). As a result, local governments manage local affairs with guidance from the central government (Tang et al., 2017). Based on the Scientific Outlook on Development of former President Hu Jintao, the China State Council proposed the Decision on Implementing the Scientific Outlook on Development and Strengthening Environmental Protection in 2006,¹ which changed China's development model. The central government places great emphasis on environmental problems which have become an essential factor in their evaluation of the local government's performance, which has become an important consideration in promoting local government officials to higher positions² (He et al., 2020).

Consequently, climate change threatens politicians' political careers. Faced with climate change, politicians have a greater incentive to supervise local firms and curb pollutant emissions to address climate change. In this study, we first examined the effect of climate change on firms' incentives to reduce pollutant emissions. We employed a pooled ordinary least squares (OLS) regression and used data from the Daily Surface Climatological Data (DSCD) between 2006 and 2013 to measure climate change, which provides China's historical surface temperature information. To measure pollutant emissions, we used the data on Chinese industrial firms above the designated size from the China Annual Survey of Industrial Firms (ASIF) database, focusing on sulfur dioxide (SO₂) emissions, which is consistent with Liu et al. (2021)

research due to the integrity and authority of SO₂ emission data. These data are monitored by the China Environmental Protection Bureau, have abundant observations and less missing value.

Climate change is induced more by air contaminants than liquid contaminants. Therefore, we examined whether environmental regulations amplify or diminish the effects of climate change on firms' pollution emission reduction efforts, both at the central and local levels, as suggested by Liu et al. (2021). Additionally, we investigated the mechanisms and approaches that firms use to reduce pollution. One approach involves changing the production process by reducing operating time, while the other approach involves "end-of-pipe" interventions, such as purchasing treatment facilities (He et al., 2020). Furthermore Acemoglu et al. (2011) and Brown et al. (2022) proposed that green innovation can be an effective way to eliminate pollutant emissions while maintaining economic competitiveness.

2. Hypothesis development

2.1. Effect of climate change on firms' pollution emission reduction efforts

Developing countries pursue economic growth at the expense of the ecological environment. Climate change accelerates the worsening of pollution, such as pollutant deterioration into more harmful contaminants, leading to serious ecological problems that have sparked widespread social concern (He et al., 2020). Moreover, climate change affects not only the ecological system but also human health (Fu et al., 2021). There is growing public pressure on the government to tighten its supervision to constrain firms' pollutant emissions and impose heavy pollution taxes and penalties. The public also requires the judicial system to punish firms when they suffer serious pollution incidents (Jaffe et al., 2002). Therefore, the government has responded to public demands by exerting pressure on firms to reduce pollution.

Climate change also increases the risk of metamorphic and secondary pollution, forcing governments to focus on this aspect. China practices a "from top to bottom" environmental regulation approach. The central government takes the lead in environmental planning and policymaking, while local governments are responsible for executing these plans (He et al., 2020). Since 2006, environmental problems have become to an essential factor in determining the career advancement of local politicians under the one-vote veto system of the 12th 5-year plan of China. Consequently, firms that emit pollutants have seriously affected the competitiveness of local government officials for political promotion. This has forced local governments to exert pressure on firms to reduce pollutant emissions. Governments must tighten their supervision and urge local firms to reduce emissions to avoid being voted down because of environmental problems. Consequently, when climate change is severe, environmental regulations may be used to prevent environmental pollution incidents.

H1: Firms reduce their pollutant emissions to address climate change.

1 Refer to the China State Council website here: http://www.gov.cn/gongbao/content/2006/content_169993.htm.

2 China State Council has proposed Opinions of The State Council on Strengthening Key Work of Environmental Protection in 2011. The action requires "One vote against" for politicians of local governments.

2.2. Effect of environmental regulations

The issue of firms' pollutant emissions has become a focus of public criticism, forcing the government to adopt environmental regulations to encourage firms to start reducing pollutant emissions. Environmental regulations by the government should address the negative externalities of environmental pollution and hold firms accountable for environmental protection (Brown et al., 2022). Environmental regulations in China are enacted by both central and local governments. The decision to implement the Scientific Outlook on Development and Strengthening Environmental Protection³ has changed China's development model, which only considers economic development. The central government has placed more weight on environmental problems in evaluating the performance of local governments. This is particularly relevant given the competition for political promotion within the different hierarchies of local governments (Piotroski et al., 2015), where local officials strive to avoid being negatively impacted by environmental issues.

Administrative power plays a significant role in firms' decision-making processes (Dong et al., 2021). The government requires firms to comply with the environmental policies of the region in which they are registered. Firms also have a strong incentive to comply with government regulations and public demands to avoid disagreements and punishments (Liu et al., 2021). Based on China's "from top to bottom" environmental regulation approach, He et al. (2020) found that firms located upstream of environmental monitoring stations in rivers reduce approximately 57% of chemical oxygen demand emissions. Chen et al. (2017) also discovered that the disclosure of environmental information by listed firms is beneficial to social welfare and environmental protection. When environmental regulations are stringent, firms place greater emphasis on environmental problems and take action to reduce pollutant emissions.

H2: Rigorous environmental regulations strengthen firms' efforts to reduce their pollutant emissions in the face of climate change.

3. Materials and methods

3.1. Data and sample

We use annual data of China's above-scale industrial firms from 2006 to 2013, and ordinary least squares (OLS) regression with province- and year- fixed effects, to investigate how climate change affects firms' pollution behavior, with a focus on environmental reregulations. Before 2006, local governments' performance was evaluated based mostly on economic indicators, and it was observed that local governments paid little attention to environmental protection. We searched the Environmental Survey and Reporting Database and the ASIF database for data up to 2013, the end year of our search.

Climate change data were downloaded from DSCD, a dataset published daily by the China National Meteorological

Administration. We converted the daily data into annual data by calculating the average for the whole year from Jan-1-2006 to Dec-31-2013. We then merged the climate change data from DSCD with firm-year data from ASIF. Data on pollutant emissions (SO₂) and firms' abatement methods were collected annually from the Environmental Survey and Reporting Database.

Country-level environmental regulation data were manually collected according to the list of "Two control zones," which were designated at the city level in 1998 by the State Council of China.⁴ We merged this list of the two control zones with the firm's location. Data on environmental regulations at the local level were obtained from two sources: The first was from the China Statistical Yearbook, published by the China National Bureau of Statistics, which provides province-level information. The second source was based on the geographical proximity to the boundaries of regions within provinces, cities, and counties, as determined using the Baidu map and the Python framework. Green innovation data were manually collected at the firm level. First, we manually collected annual information on international patent classification (IPC), which uniquely identifies the technological field of each firm, from the China State Intellectual Property Office (CSIPO) using the names of firms. We then matched the IPCs with the patent lists from the World Intellectual Property Organization (WIPO) and the Organization for Economic Co-operation and Development (OECD). The remaining data, such as size and leverage, were collected at the firm level from the ASIF database. Data on region-level variables, such as economic and population data, were obtained from the China Statistical Yearbook database.

We then deleted samples that could influence the accuracy of the regression analysis based on the recommendations by Brandt et al. (2009) and He et al. (2020). These samples included omitted observations at any variable level and those related to environmental protection facilities. A total of 29, 3,848 observations were included in our sample.

3.2. Regression model and variable definition

$$Emission_{i,t} = \beta_0 + \beta_1 Climate_{i,t} + \sum_{n=2}^N \beta_n Controls_{i,t} + Year\ FE + Province\ FE + \xi_{i,t} \quad (1)$$

To investigate how climate change affects firms' emission reduction efforts on SO₂, we used a regression model (1), where the independent variable is *Climate* and the dependent variable is *Emission*. *Year FE* and *Province FE* represent year and province fixed effects, respectively, while ξ is the stochastic error term. The specific definitions of each variable are as follows.

³ Refer to the China State Council website here: http://www.gov.cn/gongbao/content/2006/content_169993.htm.

⁴ The two control zones policy ended in 2015, which did not fall in our sample period.

TABLE 1 Variable definitions.

Variables	Unit	Level	Definition
<i>Emission</i>	Logarithm	Firm	Natural logarithm of kilograms of firms' SO ₂ emission.
<i>Detatem3</i>	Degree	Province	Mean temperature of current year minus mean temperature in the past 3 years.
<i>Detatem5</i>	Degree	Province	Mean temperature of current year minus mean temperature in the past 5 years.
<i>Size</i>	Logarithm	Firm	Natural logarithm of total assets.
<i>Lev</i>	Ratio	Firm	Total liabilities divided by total assets.
<i>Intangible</i>	Ratio	Firm	Intangible assets divided by total assets.
<i>ROA</i>	Ratio	Firm	Earnings after tax divided by total assets.
<i>Age</i>	Logarithm	Firm	Natural logarithm of current year minus establishment year.
<i>SOE</i>	Indicator	Firm	Equals 1 if the actual controller is government or its' affiliations, and 0 otherwise.
<i>Entry</i>	Logarithm	Province	Natural logarithm of the number of new entrants in the same industry and province
<i>GDP</i>	Logarithm	Province	Natural logarithm of gross domestic product at province level
<i>Structure</i>	Ratio	Province	Output value of third industry divided by GDP at province level
<i>Urban</i>	Ratio	Province	Population in urban area divided by entire population at province level
<i>Invest</i>	Logarithm	Province	Natural logarithm of government investment expenditure at province level
<i>FDI</i>	Logarithm	Province	Natural logarithm of foreign direct investment

TABLE 2 Summary statistics.

Variables	N	Mean	25%	Median	75%	SD
<i>Emission</i>	293,807	9.714	6.938	8.408	9.794	11.137
<i>Detatem3</i>	293,807	0.416	0.141	0.244	0.376	0.553
<i>Detatem5</i>	293,807	0.421	0.111	0.227	0.431	0.587
<i>Size</i>	293,807	18.100	16.097	16.927	17.946	19.130
<i>Lev</i>	293,807	0.564	0.200	0.403	0.521	0.744
<i>Intangible</i>	293,807	0.003	0.000	0.000	0.000	0.000
<i>ROA</i>	293,807	0.099	−0.021	0.000	0.030	0.120
<i>Age</i>	293,807	2.128	1.099	1.609	2.197	2.639
<i>SOE</i>	293,807	0.104	0.000	0.000	0.000	0.000
<i>Entry</i>	293,807	2.290	0.693	1.386	2.197	3.045
<i>GDP</i>	293,807	28.173	27.188	27.687	28.260	28.760
<i>Structure</i>	293,807	0.391	0.334	0.352	0.385	0.420
<i>Urban</i>	293,807	0.523	0.385	0.438	0.514	0.608
<i>Inv</i>	293,807	27.620	26.559	27.158	27.714	28.164
<i>FDI</i>	293,807	26.961	25.557	26.035	26.829	27.880

3.2.1. Climate change (Detatem3 and Detatem5)

Sea level rise was widely used in previous studies to measure climate change and its repercussions (Bernstein et al., 2019). However, the applicability of this measurement method in China remains questionable. There are two main reasons for this: first, China generally has a high terrain, especially in the central and western regions, which have mountains and plateaus. As a result, sea level rise has a limited impact on numerous non-coastal firms in the short term. Second, unlike the geographical characteristics of the United States, which is adjacent to both the Atlantic and Pacific

oceans, China is located on the western Pacific continental shelf, which has a distinct continental character, and its geographical depth makes it more resistant to the impact of sea level rise. The increasing occurrences of extreme temperatures in China have alerted the awareness for public to restrain firms' pollutant emissions. For example, the observed extreme temperatures caused by the West Pacific subtropical high in the middle and lower reaches of the Yangtze River in 2022. According to Montzka et al. (2011), the temperature increase is an appropriate measure of climate change that can be directly observed. The DSCD database,

TABLE 3 Effects of climate change on firms’ SO2 emissions.

	(1)	(2)	(3)	(4)
	<i>Emission</i>	<i>Emission</i>	<i>Emission</i>	<i>Emission</i>
<i>Detatem3</i>	−0.171***	−0.219***		
	(0.017)	(0.016)		
<i>Detatem5</i>			−0.100***	−0.167***
			(0.017)	(0.017)
<i>Size</i>		0.390***		0.390***
		(0.005)		(0.005)
<i>Lev</i>		0.586***		0.585***
		(0.024)		(0.024)
<i>Intangible</i>		−1.821***		−1.813***
		(0.279)		(0.279)
<i>ROA</i>		−0.098***		−0.099***
		(0.030)		(0.030)
<i>Age</i>		−0.067***		−0.067***
		(0.008)		(0.008)
<i>SOE</i>		0.485***		0.485***
		(0.029)		(0.029)
<i>Entry</i>		0.217***		0.217***
		(0.006)		(0.006)
<i>GDP</i>		−0.451***		−0.516***
		(0.154)		(0.155)
<i>Structure</i>		1.596***		1.588***
		(0.334)		(0.334)
<i>Urban</i>		−0.130		−0.128
		(0.498)		(0.498)
<i>Inv</i>		0.362***		0.363***
		(0.059)		(0.059)
<i>FDI</i>		−0.362***		−0.360***
		(0.045)		(0.045)
<i>Intercept</i>	9.786***	13.922***	9.757***	15.665***
	(0.010)	(4.124)	(0.010)	(4.134)
Province FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
<i>N</i>	293,807	293,807	293,807	293,807
Adj- <i>R</i> ²	0.042	0.142	0.042	0.141

*** represent the significance of the coefficient at 1% level; standard error clustered by firm is shown in the parenthesis.

which offers practical and feasible materials for studying climate change, provides annual average temperature data for various regions in China. Based on Deschenes and Greenstone (2007), we calculated the difference between the average temperature of each city in the current year and the average temperature of the past 3 and 5 years. The larger the value, the greater the climate change.

TABLE 4 Alternate measurement of SO2 emissions.

	(1)	(2)
	<i>Emission2</i>	<i>Emission2</i>
<i>Detatem3</i>	−3.995***	
	(0.437)	
<i>Detatem5</i>		−1.886***
		(0.426)
<i>Size</i>	−3.892***	−3.894***
	(0.091)	(0.091)
<i>Lev</i>	1.933***	1.912***
	(0.559)	(0.559)
<i>Intangible</i>	−52.477***	−52.417***
	(8.489)	(8.489)
<i>ROA</i>	−8.130***	−8.146***
	(0.652)	(0.652)
<i>Age</i>	−1.135***	−1.139***
	(0.187)	(0.187)
<i>SOE</i>	8.117***	8.108***
	(0.596)	(0.596)
<i>Entry</i>	2.993***	2.992***
	(0.126)	(0.126)
<i>GDP</i>	−7.063*	−8.852**
	(3.743)	(3.751)
<i>Structure</i>	60.858***	59.712***
	(8.026)	(8.042)
<i>Urban</i>	15.966	17.052
	(10.496)	(10.521)
<i>Inv</i>	−5.587***	−5.817***
	(1.355)	(1.361)
<i>FDI</i>	−8.350***	−8.347***
	(1.226)	(1.226)
<i>Intercept</i>	633.325***	689.063***
	(97.239)	(97.774)
Province FE	Y	Y
Year FE	Y	Y
<i>N</i>	293,807	293,807
Adj- <i>R</i> ²	0.069	0.068

*, **, and *** represent the significance of the coefficient at 10, 5, and 1%, respectively; standard error clustered by firm is shown in the parenthesis.

3.2.2. Firms’ pollution behavior (Emission)

We used SO₂ emissions to measure firms’ pollution behavior based on the recommendations by Liu et al. (2021). SO₂ is a primary contaminant that causes acidification, which is harmful to natural resources and directly contributes to human health issues (Liu et al., 2021). First, since climate change is calculated according to

TABLE 5 Change the definition of independent variables.

	(1)	(2)	(3)	(4)	(5)	(6)
	<i>Emission</i>	<i>Emission</i>	<i>Emission</i>	<i>Emission</i>	<i>Emission</i>	<i>Emission</i>
<i>Detatem4</i>	−0.216*** (0.017)					
<i>Detatem6</i>		−0.172*** (0.017)				
<i>Act_temp3</i>			−0.066*** (0.008)			
<i>Act_temp5</i>				−0.062*** (0.008)		
<i>Ext_tem3</i>					−0.068*** (0.008)	
<i>Ext_tem5</i>						−0.067*** (0.008)
<i>Size</i>	0.390*** (0.005)	0.390*** (0.005)	0.391*** (0.005)	0.391*** (0.005)	0.391*** (0.005)	0.391*** (0.005)
<i>Lev</i>	0.586*** (0.024)	0.585*** (0.024)	0.581*** (0.024)	0.581*** (0.024)	0.582*** (0.024)	0.581*** (0.024)
<i>Intangible</i>	−1.811*** (0.279)	−1.806*** (0.279)	−1.817*** (0.279)	−1.839*** (0.279)	−1.835*** (0.279)	−1.839*** (0.279)
<i>ROA</i>	−0.099*** (0.030)	−0.099*** (0.030)	−0.104*** (0.030)	−0.102*** (0.030)	−0.103*** (0.030)	−0.103*** (0.030)
<i>Age</i>	−0.067*** (0.008)	−0.067*** (0.008)	−0.066*** (0.008)	−0.066*** (0.008)	−0.066*** (0.008)	−0.066*** (0.008)
<i>SOE</i>	0.485*** (0.029)	0.485*** (0.029)	0.475*** (0.029)	0.476*** (0.029)	0.474*** (0.029)	0.475*** (0.029)
<i>Entry</i>	0.217*** (0.006)	0.217*** (0.006)	0.217*** (0.006)	0.217*** (0.006)	0.217*** (0.006)	0.217*** (0.006)
<i>GDP</i>	−0.463*** (0.155)	−0.508*** (0.155)	−0.600*** (0.154)	−0.607*** (0.154)	−0.606*** (0.154)	−0.603*** (0.154)
<i>Structure</i>	1.624*** (0.334)	1.597*** (0.335)	1.407*** (0.333)	1.458*** (0.333)	1.389*** (0.333)	1.411*** (0.333)
<i>Urban</i>	−0.211 (0.498)	−0.219 (0.499)	0.134 (0.497)	−0.105 (0.497)	0.041 (0.497)	−0.002 (0.497)
<i>Inv</i>	0.368*** (0.059)	0.368*** (0.059)	0.321*** (0.059)	0.330*** (0.059)	0.326*** (0.059)	0.327*** (0.059)
<i>FDI</i>	−0.365*** (0.045)	−0.362*** (0.045)	−0.347*** (0.045)	−0.360*** (0.045)	−0.352*** (0.045)	−0.354*** (0.045)
<i>Intercept</i>	14.234*** (4.134)	15.395*** (4.136)	19.684*** (4.110)	20.035*** (4.115)	19.942*** (4.112)	19.878*** (4.112)
Province FE	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y
<i>N</i>	293,807	293,807	293,807	293,807	293,807	293,807
Adj- <i>R</i> ²	0.141	0.141	0.142	0.142	0.142	0.142

***represent the significance of the coefficient at 1% level; standard error clustered by firm is shown in the parenthesis.

temperature changes in a specific region, it is more closely related to air contaminants than liquid contaminants. SO₂ emissions destroy the atmosphere and lead to numerous pollution incidents. Acidification and photochemical smog may have severe negative effects on public health and result in significant ecological damage. Second, SO₂ emissions are better monitored in comparison to other air contaminants, such as industrial dust and nitric oxide, and have fewer omitted observations in the Environmental Survey and Reporting Database, guaranteeing a certain level of data quality for our sample (Liu et al., 2021).

We measured pollution using the natural logarithm of kilograms of SO₂ emissions, following Akey and Appel (2021). We excluded observations where SO₂ emissions were equal to zero because it was difficult to distinguish whether the value was a genuine zero or omitted, which may have introduced noise into our research. Furthermore, we followed the approach recommended by Liu et al. (2021) and calculated a relative number by dividing the kilograms of SO₂ emission by the constant price of gross industrial output, adjusted for inflation, in the robustness check.

3.2.3. Control variables (Controls)

The control variables consisted of both firm-specific and city-level variables, which may have affected firms' emission behavior, as recommended by Brandt et al. (2009) and He et al. (2020). Table 1 presents the definitions of the control variables.

4. Results

4.1. Summary statistics

Table 2 shows that the mean value of *Emission* is 9.714, which implies that, during our sampling period, firms released an average of 16, 547 kg of SO₂ annually. The means of *Detatem3* and *Detatem5* were 0.416 and 0.421, respectively, indicating that, on average, the temperature of the current year is higher than that in the past 3 and 5 years. This is consistent with the overall trend of increasing temperatures. The other control variables in our study were consistent with those of prior research (He et al., 2020).

4.2. Baseline results

Table 3 shows how climate change affects firms' SO₂ emissions behavior. Columns (1) and (3) excluded the control variables, whereas columns (2) and (4) included them. Regardless of whether the independent variable was *Detatem3* or *Detatem5*, the coefficients among the four columns were negative and significant at the 1% level. Considering the example of column (2), a unit of *Detatem3* increase led to an emission reduction of 6.18% [$0.220 \times (11.137 - 8.4.8)/9.714$] from the 25th percentile to the 75th percentile, indicating that an increase in climate change bolstered firms' efforts to mitigate SO₂ emissions. Thus, Hypothesis 1 was confirmed.

The results for the control variables are as follows: The coefficient of *Size* was significantly positive, suggesting that big firms had to engage in more productive activities to maintain their

going-concern status, compensate for marginally increasing costs, and consequently produce more SO₂ emissions. The coefficient of *Lev* was significantly positive, suggesting that firms with large financial leverage undertook more obligations to pay off their debt; therefore, they created more cash flow by increasing productivity at the expense of the environment. The coefficient of *Intangible* was significantly negative, indicating that a greater number of innovative firms were equipped to improve production efficiency while using fewer resources and emitting less pollution. The coefficient of *ROA* was significantly negative. High economic efficiency is benefit for going green. The coefficient of *Age* was significantly negative, indicating that startups lag behind compared to incumbents. The coefficient of *SOE* was significantly positive, indicating that state-owned firms were less worried about their pollution behavior due to government assurance and having more capital resources to increase their scale, leading to more pollution (Allen et al., 2005). The coefficient of *Entry* was significantly positive, indicating that new market entrants faced resistance from incumbents who preferred to increase their productivity to occupy the marketplace, leading to more SO₂ emissions (Aghion et al., 2001). Variables at the province level indicated that *GDP* and *FDI* were negatively correlated with SO₂ emissions, whereas *Inv* was positively correlated with SO₂ emissions, which is consistent with the findings presented by Li and Zhou (2005), Chen et al. (2017), He et al. (2020), and Liu et al. (2021).

4.3. Robustness check

4.3.1. Alternate measurements of SO₂ emissions

Following the recommendations of Liu et al. (2021), we replaced the dependent variable with a relative indicator of SO₂ emission, which was adjusted by the industrial output value. Table 4 shows that *Detatem3* and *Detatem5* in columns (1)–(2) are both negative and significant at the 1% level, ensuring the robustness of our main results.

4.3.2. Alternate measurements of climate change

We made several revisions to our measurement of climate change. First, we modified the calculation window period of the core independent variable to 4 and 6 years, referred to as *Detatem4* and *Detatem6*, respectively. Subsequently, we included the mean and the highest temperature of each city over the past 3 years as *Act_temp3* and *Ext_temp3*, respectively, as well as over the past 5 years as *Act_temp5* and *Ext_temp5*, respectively. Table 5 illustrates that all coefficients of the alternative, independent variables were negatively significant at the 1% level, confirming the robustness of our baseline results.

4.3.3. Change the time series

We then tested whether firms' SO₂ emissions in the current year were influenced by climate change in the previous year. Table 6 illustrates that both lags of *Datatem3* and *Datetem5* were negative and significant at the 1% level, confirming the robustness of our baseline results.

TABLE 6 Change in the time series.

	(1)	(2)
	<i>Emission</i>	<i>Emission</i>
<i>Detatem3 (T-1)</i>	−0.203*** (0.020)	
<i>Detatem5 (T-1)</i>		−0.108*** (0.023)
<i>Size (T-1)</i>	0.420*** (0.006)	0.420*** (0.006)
<i>Lev (T-1)</i>	0.586*** (0.027)	0.584*** (0.027)
<i>Intangible (T-1)</i>	−1.808*** (0.292)	−1.803*** (0.293)
<i>ROA (T-1)</i>	−0.096*** (0.035)	−0.098*** (0.035)
<i>Age (T-1)</i>	−0.103*** (0.009)	−0.103*** (0.009)
<i>SOE (T-1)</i>	0.459*** (0.033)	0.458*** (0.033)
<i>Entry (T-1)</i>	0.219*** (0.007)	0.219*** (0.007)
<i>GDP (T-1)</i>	−0.222 (0.193)	−0.283 (0.193)
<i>Structure (T-1)</i>	2.577*** (0.406)	2.550*** (0.406)
<i>Urban (T-1)</i>	−0.417 (0.596)	−0.270 (0.598)
<i>Inv (T-1)</i>	0.348*** (0.069)	0.332*** (0.069)
<i>FDI (T-1)</i>	−0.546*** (0.056)	−0.530*** (0.056)
<i>Intercept</i>	12.268** (5.292)	13.890*** (5.295)
Province FE	Y	Y
Year FE	Y	Y
N	191,059	191,059
Adj-R ²	0.156	0.156

, and * represent the significance of the coefficient at 5, and 1%, respectively; standard error clustered by firm is shown in the parenthesis.

4.3.4. Difference model

We attempted to overcome the problem of omitted variables by using the change model, following the recommendations by Chen et al. (2018), which involved regressing the difference between the current year and the previous year for all variables. Table 7 shows the negative coefficients at the 1%

TABLE 7 Regression of the change model.

	(1)	(2)
	Δ <i>Emission</i>	Δ <i>Emission</i>
Δ <i>Detatem3</i>	−0.023*** (0.009)	
Δ <i>Detatem5</i>		−0.026*** (0.008)
Δ <i>Size</i>	0.043*** (0.006)	0.043*** (0.006)
Δ <i>Lev</i>	0.009 (0.012)	0.009 (0.012)
Δ <i>Intangible</i>	−0.060 (0.178)	−0.058 (0.177)
Δ <i>ROA</i>	0.057*** (0.015)	0.057*** (0.015)
Δ <i>Age</i>	0.036*** (0.010)	0.036*** (0.010)
Δ <i>SOE</i>	0.033 (0.030)	0.034 (0.030)
Δ <i>Entry</i>	0.008 (0.008)	0.008 (0.008)
Δ <i>GDP</i>	−0.446*** (0.152)	−0.431*** (0.152)
Δ <i>Structure</i>	−0.598** (0.269)	−0.564** (0.271)
Δ <i>Urban</i>	−0.891** (0.410)	−0.879** (0.410)
Δ <i>Inv</i>	−0.078 (0.050)	−0.071 (0.050)
Δ <i>FDI</i>	0.105*** (0.032)	0.107*** (0.032)
<i>Intercept</i>	0.072*** (0.022)	0.067*** (0.022)
Province FE	Y	Y
Year FE	Y	Y
N	191,059	191,059
Adj-R ²	0.002	0.002

, and * represent the significance of the coefficient at 5, and 1% respectively; standard error clustered by firm is shown in the parenthesis.

significance level for *Detatem3* (column 1) and *Detatem5* (column 2). As the temperatures rose, firms acted to reduce their SO₂ emissions, confirming the robustness of our baseline results.

TABLE 8 Climate change and CO2 emissions at the province level.

	(1)	(2)	(3)	(4)
	CO2_Emission1	CO2_Emission1	CO2_Emission2	CO2_Emission2
Detatem3	−0.004*** (0.001)		−0.036*** (0.008)	
Detatem5		−0.007*** (0.001)		−0.055*** (0.008)
Size	0.000 (0.000)	0.000 (0.000)	0.042*** (0.002)	0.042*** (0.002)
Lev	0.002*** (0.000)	0.002*** (0.000)	0.158*** (0.010)	0.159*** (0.010)
Intangible	−0.029*** (0.008)	−0.029*** (0.008)	−2.109*** (0.182)	−2.105*** (0.182)
ROA	0.001 (0.001)	0.001 (0.001)	−0.052*** (0.011)	−0.053*** (0.011)
Age	−0.000 (0.000)	−0.000 (0.000)	0.003 (0.004)	0.003 (0.004)
SOE	0.002*** (0.000)	0.002*** (0.000)	−0.092*** (0.012)	−0.092*** (0.012)
Entry	−0.000*** (0.000)	−0.000*** (0.000)	0.031*** (0.003)	0.031*** (0.003)
GDP	0.348*** (0.012)	0.349*** (0.012)	−1.009*** (0.033)	−1.012*** (0.033)
Structure	−0.500*** (0.016)	−0.496*** (0.016)	0.177 (0.124)	0.191 (0.124)
Urban	0.592*** (0.020)	0.588*** (0.020)	2.228*** (0.058)	2.236*** (0.058)
Inv	0.147*** (0.003)	0.148*** (0.003)	1.084*** (0.029)	1.089*** (0.029)
FDI	−0.000 (0.002)	−0.000 (0.002)	−0.646*** (0.010)	−0.647*** (0.010)
Intercept	−8.172*** (0.328)	−8.235*** (0.329)	15.919*** (0.280)	15.885*** (0.281)
Province FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
N	293,807	293,807	293,807	293,807
Adj-R ²	0.992	0.992	0.562	0.563

***represent the significance of the coefficient at 1% respectively; standard error clustered by firm is shown in the parenthesis.

4.3.5. Evidence from CO₂ emissions at the province level

Furthermore, we examined the impact of climate change on carbon dioxide emissions at the provincial level.⁵ To measure

5 Because of a lack of data, we could not obtain data on carbon dioxide emission at the firm level. China’s disclosure regulations on carbon emissions were weak, especially for the unlisted firms (Chen et al., 2017).

CO₂ emissions, we employed the following two approaches: the natural logarithm of the amount of CO₂ emissions in kilograms for every province (*CO2_Emission1*) and the ratio of kilograms of CO₂ emissions to total assets for every province (*CO2_Emission2*).

Table 8 illustrates that the coefficients of *Detatem3* and *Detatem5* were negatively correlated with CO₂ emissions, confirming the robustness of our results.

TABLE 9 Cross-sectional test of environmental regulations at the central level.

	(1)	(2)	(3)	(4)
	<i>Emission</i>	<i>Emission</i>	<i>Emission</i>	<i>Emission</i>
<i>Detatem3</i>	−0.164*** (0.018)	−0.029 (0.022)		
<i>Detatem5</i>			−0.028 (0.018)	0.006 (0.024)
<i>Acid</i>	−0.327*** (0.027)		−0.228*** (0.027)	
<i>SO₂_control</i>		−0.120*** (0.018)		−0.122*** (0.018)
<i>Acid_control</i> × <i>Detatem3</i>	−0.109*** (0.033)			
<i>SO₂_control</i> × <i>Detatem3</i>		−0.078*** (0.028)		
<i>Acid_control</i> × <i>Detatem5</i>			−0.350*** (0.036)	
<i>SO₂_control</i> × <i>Detatem5</i>				−0.075** (0.030)
<i>Size</i>	0.393*** (0.005)	0.408*** (0.005)	0.393*** (0.005)	0.408*** (0.005)
<i>Lev</i>	0.585*** (0.023)	0.370*** (0.020)	0.586*** (0.023)	0.369*** (0.020)
<i>Intangible</i>	−1.817*** (0.279)	−0.388 (0.243)	−1.794*** (0.279)	−0.386 (0.243)
<i>ROA</i>	−0.121*** (0.030)	0.125*** (0.026)	−0.122*** (0.030)	0.125*** (0.026)
<i>Age</i>	−0.059*** (0.008)	0.026*** (0.007)	−0.059*** (0.008)	0.026*** (0.007)
<i>SOE</i>	0.477*** (0.029)	0.299*** (0.025)	0.476*** (0.029)	0.299*** (0.025)
<i>Entry</i>	0.227*** (0.006)	0.026*** (0.006)	0.226*** (0.006)	0.026*** (0.006)
<i>GDP</i>	−0.469*** (0.155)	−0.044 (0.034)	−0.512*** (0.155)	−0.039 (0.034)
<i>Structure</i>	1.443*** (0.334)	−0.054 (0.184)	1.365*** (0.334)	−0.054 (0.184)
<i>Urban</i>	−0.400 (0.497)	−1.589*** (0.109)	−0.068 (0.499)	−1.616*** (0.109)
<i>Inv</i>	0.361*** (0.059)	0.252*** (0.038)	0.329*** (0.059)	0.243*** (0.038)
<i>FDI</i>	−0.363*** (0.045)	−0.081*** (0.016)	−0.362*** (0.045)	−0.077*** (0.016)

(Continued)

TABLE 9 (Continued)

	(1)	(2)	(3)	(4)
	<i>Emission</i>	<i>Emission</i>	<i>Emission</i>	<i>Emission</i>
<i>Intercept</i>	14.760***	−0.611	16.630***	−0.581
	(4.136)	(0.454)	(4.134)	(0.454)
Province FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
<i>N</i>	293,807	293,807	293,807	293,807
Adj- <i>R</i> ²	0.144	0.349	0.144	0.349

** and *** represent the significance of the coefficient 5, and 1%, respectively; standard error clustered by firm is shown in the parenthesis.

5. Cross-sectional tests

China has a large territory, which makes it difficult for the government to adequately address the environmental issues of the entire country. To address this issue, local governments are responsible for executing environmental policies within their respective jurisdictions, which are guided by the central government's principles of protecting the environment (Fu et al., 2021).

Political incentives are essential for promoting environmental protection and recovery (Acemoglu and Robinson, 2013). According to the public choice theory, political decisions are based on the balance of cost and benefit for politicians (Buchanan, 1983), while the goal of obtaining as many votes as possible is a top priority for them. As the sole ruling party in China, the Community Party of China places great importance on improving public welfare in its governance of the whole country. Therefore, the central government should regulate firms' emission behavior to benefit public health. The central government assigns regulatory functions to local governments and monitors local governments' environmental protection performance, which is essential for local politicians' promotions. In this way, local politicians are incentivized to constrain pollutant emissions by requiring firms to obey local environmental policies. We examined cross-sectional data to evaluate the effectiveness of environmental regulations by both the central and local governments.

5.1. Environmental regulations at the country level

Several studies have attempted to determine how environmental regulations implemented by the Chinese central government can help achieve emission reduction targets. For example, He et al. (2020) utilized water quality monitoring stations located in the rivers of China and found lower chemical oxygen demand emissions upstream rather than downstream. Liu et al. (2021) examined the "Two control zones" designated by the Chinese central government and found that stronger regulations led to reduced pollutant emissions for firms facing earnings pressure. The central government has formulated environmental policies and appraisal programs at the national level (He et al.,

2020). In this study, we manually collected data on acid and SO₂ from the "Two control zones."

Table 9 shows that the coefficients of the interaction terms *Acid_control* × *Detatem3*, *SO₂_control* × *Detatem3*, *Acid_control* × *Detatem5*, and *SO₂_control* × *Detatem5* were negative and significant at the 1% level, illustrating that stronger environmental regulations implemented by the central government led to a greater reduction in SO₂ emissions among firms facing climate change.

5.2. Environmental regulations at the local level

5.2.1. The strength of environmental regulations by local governments

In China, local governments implement environmental policies and formulate local regulations with regional characteristics. China is a large country and, therefore, it is difficult for the central government to comprehensively collect and disseminate information to the entire country (Hayek, 1945). In addition, local customs and interest preferences vary across different local areas, making it difficult to impose inflexible regulations uniformly across the country. To address this issue, various local governments manage local areas and execute laws and regulations. The central government has established measures to evaluate local governments' performance in local development (Li and Zhou, 2005).

The Scientific Outlook on Development has had a profound effect on China's economic growth by emphasizing the importance of environmental protection in evaluating local governments' performance. Consequently, local officers generally implement stronger environmental regulations to reduce pollutant emissions from firms. Additionally, local fiscal authorities are responsible for assessing environmental damage and developing various environmental prevention measures. We investigated how the strength of local environmental regulations affects the reduction of SO₂ emissions caused by climate change. According to previous research, the strength of environmental regulations can be assessed by evaluating investments in addressing regional environmental pollution at the provincial level (Berman and Bui, 2001). Specifically, we identified the median value among all provinces per year, and samples above the median value indicated

that the firms' location is subject to stringent environmental regulations. We used an indicator variable, *ER*, that equals 1 if regulations are stringent or 0 otherwise.

Table 10 shows that the interaction terms $ER \times Detatem3$ and $ER \times Detatem5$ were negative at the 1% significance level. The more stringent the environmental regulations, the greater the reduction in SO_2 emissions due to climate change.

5.2.2. Boundary effect of local governments' environmental regulations

Local governments are limited in their ability to enforce environmental regulations. First, fierce competition among local governments in the same rank aggravates their short-sighted behaviors and makes them prefer beggar-thy-neighbor policies that only benefit them and undermine neighboring provinces (Li and Zhou, 2005). Second, there is an information asymmetry between local and central governments, aggravating local governments' opportunistic behaviors (Piotroski et al., 2015). Economic growth and environmental protection are two major factors determining local government officials' likelihood of promotion. However, the inherent contradiction between economic and environmental indicators is difficult to mediate (Acemoglu et al., 2011).

Previous studies found that local governments improve local economic indicators at the cost of the welfare of surrounding areas, especially along provincial boundaries (Sigman, 2005). However, pollutants are mobile and diffusive (Akey and Appel, 2021). Pollutants released at the boundaries of administrative regions spread to other areas through the air, water, and other channels, resulting in the spillover effects of pollution. Economic figures and tax benefits generated by polluting firms are captured by local governments, while environmental governance costs spill over to other administrative regions. Therefore, to improve their own economic indicators and disperse environmental costs, local governments tend to strengthen environmental regulations on firms located far from the borders and relax environmental regulations on firms located close to the borders. We first identified the latitude and longitude of the firms based on the Baidu map and calculated their geographical distance to the nearest provincial border. We then identified whether the firms were closer to the province, city, or county border. Firms closer to the border, that is, whose distance from the border is below the median of all firms in the same region, were subject to fewer local government environmental regulations. *Near_province*, *Near_city*, and *Near_county* were 1 if the firms were near the border or 0 otherwise.

The results shown in Table 11 confirm our inference. At the provincial boundary level, the coefficients of interaction terms $Near\_province \times Detatem3$ and $Near\_province \times Detatem5$ in columns (1) and (4) were significantly positive at the 1% level. Moreover, the sum of $Near\_province \times Detatem5$ and $Near\_province$ was positive, indicating that climate change has a positive influence on firms' SO_2 emissions when they are near the provincial boundary. These firms emit more SO_2 compared to firms that are far from the province boundary. The results are also supported by the evidence at the city and county levels of boundaries where the coefficients for $Near\_city \times Detatem3$,

TABLE 10 The effect of the strength of environmental regulations.

	(1)	(3)
	<i>Emission</i>	<i>Emission</i>
<i>ER</i>	−0.181*** (0.017)	−0.149*** (0.017)
<i>Detatem3</i>	−0.034* (0.018)	
$ER \times Detatem3$	−0.137*** (0.032)	
<i>Detatem5</i>		0.038** (0.018)
$ER \times Detatem5$		−0.199*** (0.031)
<i>ER</i>	−0.181*** (0.017)	−0.149*** (0.017)
<i>Size</i>	0.406*** (0.005)	0.406*** (0.005)
<i>Lev</i>	0.369*** (0.020)	0.367*** (0.020)
<i>Intangible</i>	−0.378 (0.243)	−0.382 (0.243)
<i>ROA</i>	0.138*** (0.026)	0.138*** (0.026)
<i>Age</i>	0.021*** (0.007)	0.021*** (0.007)
<i>SOE</i>	0.299*** (0.025)	0.298*** (0.025)
<i>Entry</i>	0.011* (0.006)	0.011* (0.006)
<i>GDP</i>	−0.008 (0.034)	−0.012 (0.034)
<i>Structure</i>	−0.605*** (0.184)	−0.622*** (0.184)
<i>Urban</i>	−1.390*** (0.109)	−1.411*** (0.109)
<i>Inv</i>	0.179*** (0.038)	0.176*** (0.038)
<i>FDI</i>	−0.068*** (0.015)	−0.062*** (0.015)
<i>Intercept</i>	0.209 (0.451)	0.249 (0.451)
Province FE	Y	Y
Year FE	Y	Y
<i>N</i>	293,801	293,801
Adj- <i>R</i> ²	0.350	0.350

*, **, and *** represent the significance of the coefficient at 10, 5, and 1%, respectively; standard error clustered by firm is shown in the parenthesis.

TABLE 11 Cross-sectional test of environmental regulations at the local level.

	(1)	(2)	(3)	(4)	(5)	(6)
	<i>Emission</i>	<i>Emission</i>	<i>Emission</i>	<i>Emission</i>	<i>Emission</i>	<i>Emission</i>
<i>Detatem3</i>	−0.199***	−0.129***	−0.134***			
	(0.020)	(0.020)	(0.020)			
<i>Near_province</i>	−0.120***			−0.143***		
	(0.017)			(0.017)		
<i>Near_province</i> × <i>Detatem3</i>	0.242***					
	(0.028)					
<i>Near_city</i>		−0.021			−0.009	
		(0.017)			(0.017)	
<i>Near_city</i> × <i>Detatem3</i>		0.093***				
		(0.028)				
<i>Near_county</i>			−0.198***			−0.184***
			(0.017)			(0.017)
<i>Near_county</i> × <i>Detatem3</i>			0.101***			
			(0.028)			
<i>Detatem5</i>				−0.193***	−0.082***	−0.079***
				(0.021)	(0.021)	(0.021)
<i>Near_province</i> × <i>Detatem5</i>				0.294***		
				(0.029)		
<i>Near_city</i> × <i>Detatem5</i>					0.065**	
					(0.029)	
<i>Near_county</i> × <i>Detatem5</i>						0.065**
						(0.030)
<i>Size</i>	0.407***	0.407***	0.410***	0.407***	0.407***	0.410***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
<i>Lev</i>	0.371***	0.371***	0.372***	0.370***	0.371***	0.371***
	(0.020)	(0.020)	(0.020)	(0.020)	(0.020)	(0.020)
<i>Intangible</i>	−0.381	−0.366	−0.391	−0.375	−0.368	−0.390
	(0.243)	(0.243)	(0.243)	(0.243)	(0.244)	(0.243)
<i>ROA</i>	0.125***	0.127***	0.121***	0.124***	0.127***	0.121***
	(0.026)	(0.026)	(0.026)	(0.026)	(0.026)	(0.026)
<i>Age</i>	0.021***	0.021***	0.022***	0.020***	0.020***	0.022***
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
<i>SOE</i>	0.298***	0.300***	0.308***	0.298***	0.300***	0.308***
	(0.025)	(0.025)	(0.025)	(0.025)	(0.025)	(0.025)
<i>Entry</i>	0.016**	0.016**	0.016***	0.016**	0.016**	0.016***
	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)
<i>GDP</i>	−0.039	−0.045	−0.049	−0.035	−0.042	−0.046
	(0.034)	(0.034)	(0.034)	(0.034)	(0.034)	(0.034)
<i>Structure</i>	−0.362**	−0.315*	−0.344*	−0.363**	−0.314*	−0.343*
	(0.184)	(0.184)	(0.184)	(0.184)	(0.184)	(0.184)
<i>Urban</i>	−1.356***	−1.377***	−1.337***	−1.370***	−1.402***	−1.363***
	(0.110)	(0.109)	(0.109)	(0.110)	(0.109)	(0.109)

(Continued)

TABLE 11 (Continued)

	(1)	(2)	(3)	(4)	(5)	(6)
	<i>Emission</i>	<i>Emission</i>	<i>Emission</i>	<i>Emission</i>	<i>Emission</i>	<i>Emission</i>
<i>Inv</i>	0.244*** (0.038)	0.253*** (0.038)	0.263*** (0.038)	0.237*** (0.038)	0.247*** (0.038)	0.256*** (0.038)
<i>FDI</i>	−0.103*** (0.016)	−0.105*** (0.016)	−0.101*** (0.016)	−0.101*** (0.016)	−0.102*** (0.016)	−0.098*** (0.015)
<i>Intercept</i>	0.092 (0.20)	0.002 (0.00)	−0.255 (−0.56)	0.113 (0.25)	0.017 (0.04)	−0.237 (−0.52)
Province FE	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y
<i>N</i>	293,801	293,801	293,801	293,801	293,801	293,801
Adj- <i>R</i> ²	0.349	0.348	0.350	0.349	0.348	0.350

*, **, and *** represent the significance of the coefficient at 10, 5, and 1%, respectively; standard error clustered by firm is shown in the parenthesis.

Near_city × *Detatem5*, *Near_county* × *Detatem3*, and *Near_county* × *Detatem5* were significantly positive at the 1% level.

6. Additional tests: Emission reduction efforts

Is environmental protection detrimental or beneficial to firms' competitiveness? The relationship between environmental protection and economic growth indicates that environmental regulations and firms' efforts to reduce pollutants have two aspects. Rugman and Verbeke (1998) proposed an analytical framework for understanding how firms mitigate environmental risks and comply with regulations. From a conflict viewpoint, environmental risks and regulations may restrict firms' competitiveness, leading to a trade-off between economic growth and environmental protection (Clarkson et al., 2004). The static conflict view suggests that firms only passively mitigate environmental risks and comply with regulations, which makes it difficult to identify and capture potential green development opportunities (Gray and Shadbegian, 2003). However, the dynamic conflict view suggests that firms implement measures actively to reduce the negative impact of environmental risks and regulations on economic performance, but they do not commit to green development (Walley, 1994). As the concept of "green development" has become the consensus of all members of society, the possibility that environmental regulations and economic performance complement each other has attracted wider attention (Buyse and Verbeke, 2003). According to the static coordination view, firms proactively invest in environmental protection to simultaneously protect the environment and maintain their own economic interests. According to the dynamic coordination view, a compensation effect occurs when firms are devoted to green innovation by reducing negative externalities. Through green innovation, firms create unique green competitive advantages and generate additional economic benefits, leading to environmental risks and regulations (Porter and Linde, 1995). Based on the aforementioned four different views,

Rugman and Verbeke (1998) believe that environmental risks and regulations have various impacts on firms. Examining the measures that managers implement to cope with environmental risks and regulations can clarify whether environmental protection and economic performance are complementary or incompatible.

According to previous studies, to address climate change and environmental regulation pressure, firms implement measures such as constraining pollution productivity processes (e.g., directly reducing input and pollutant emission) and implementing "end-of-pipe" interventions (e.g., purchasing environmental protection equipment to achieve terminal control of pollutant emission) (He et al., 2020). Clarke et al. (1994) believe that firms facing environmental problems (e.g., climate change) and regulatory pressure need a breakthrough in product and technology innovation rather than passively accepting these challenges. Green innovation can create a harmonious coexistence between environmental protection and economic growth for firms (Brown et al., 2022) and can be incorporated into the production process. Firms' green technology advantage creates barriers to entry, which helps firms maintain green market competitiveness and drives them to produce new green kinetics for continuous development (Acemoglu et al., 2011).

In this study, we explored how firms approach environmental protection measures in the face of climate change and environmental regulations. Drawing on previous research such as that by Acemoglu et al. (2011) and He et al. (2020), we identified three strategies that firms devise to reduce pollution. First, firms should aim to reduce the input of production factors that contribute to pollution. This involves measures such as shortening the production process and reducing energy consumption, which, in turn, reduces the emission of toxic SO₂. Second, through "end-of-pipe" interventions, firms should invest in environmental protection equipment and expand the capacity of their equipment to deal with waste. Finally, firms should invest in green innovation to develop more green patents.

6.1. Reducing pollutive productivity process

Table 12 shows how climate change helps firms reduce pollution by reducing production factor inputs. Columns (1) and (2) used the natural logarithm of the enterprise's annual production hours as the dependent variable. Columns (3) and (4) used the natural logarithm of firms' annual coal tonnage as the dependent variable. The results showed that the coefficients of *Detatem3* and *Detatem5* were all significantly negative, indicating that the greater the climate change, the fewer the annual production hours of firms and the energy consumption of coal. Therefore, the results confirmed that firms generally address climate change and environmental regulations by reducing the input of production factors in the productivity process.

6.2. Investing in the improvement of the ability to reduce pollutant emissions

Table 13 shows whether firms adopted the end-of-pipe intervention strategy by investing in environmental protection equipment to reduce contaminant emissions in the face of climate change. The dependent variable in columns (1) and (2) was the natural logarithm of the number of environmental protection equipment of the firm. The independent variable in columns (3) and (4) was the unit capacity of the environmental protection equipment to tackle contaminants, which is the unit indicator of the end-of-pipe intervention. The results showed that the coefficients of climate change are significantly positive, suggesting that firms increased their environmental protection investments, including purchasing equipment and improving their capacity, to reduce emissions as climate change intensifies.

6.3. Green innovation

The existing studies used the number of patents successfully applied for by firms in the current year as the measurement of innovation capability; that is, the applications applied for by firms in the current year are eventually approved in the future (Moshirian et al., 2021). Following this approach, we used an authoritative list to identify green patents and then examined whether firms successfully innovate more green patents in the face of climate change. The WIPO and OECD have put forward lists identifying whether a patent is green. The WIPO green patent list is based on the patent's IPC, while the OECD green patent list is based on both the patent's IPC and Communist Party of China classification. However, China's patent system only adopts the IPC number of CSIPO. Therefore, this study followed the recommendations by Cohen et al. (2020) and adopted the IPC number in the green patent classification of the OECD.

We manually collected the IPC number from green patent classification lists issued by WIPO and OECD and then searched for the IPC classification of each enterprise's patent from the CSIPO

website. We matched the aforementioned three datasets to identify whether a given patent was green and then examined whether it was authorized by CSIPO. We retained green patents applied for by firms in the current year and eventually granted them in future years under two sets of green patent classification criteria. We summarized them at the firm-year level and transferred them to one plus the natural logarithm. However, we did not find any evidence that climate change improves firms' green innovation. Table 14 shows that the coefficients of *Detatem3* and *Detatem5* were insignificant.

The results in Tables 12–14 showed that, faced with climate change and environmental regulatory pressures, firms resort to reducing factor input and expanding investment in environmental protection rather than actively engaging in green innovation to achieve technological breakthroughs. Our findings are similar to those of Cohen and Zarowin (2010) and Liu et al. (2021), who found that, when facing pressure, firms tend to prioritize short-term gains over long-term benefits.

7. Discussion and conclusion

7.1. Discussion

This study examined the impact of climate change on firms' pollutant emissions in China. Climate change raises awareness among the public and government regarding environmental problems. China's environmental regulations are led by the central government, while local governments implement the central government's guidelines. Since environmental problems have become a important factor for local politicians to advance in their careers, the government has mandated that firms adhere to environmental regulations to avoid being outvoted. Therefore, firms have been compelled to reduce pollutant emissions to avoid incurring social and political costs and to maintain their relationships with local governments.

This study contributes to the existing literature in the following ways: First, this study bridges the gap in the literature regarding the effect of climate change on firm behavior. Prior research mainly focused on the adverse effects of climate change on firms' behavior, such as reduced productivity (Fu et al., 2021), lower stock market returns (Bolton and Kacperczyk, 2021), altered asset pricing (Barnett et al., 2020), and changes in investment decisions (Pástor et al., 2021). However, there was little research on how climate change affects firms' green efforts. Therefore, using temperature data, environmental regulations, and firms' pollutant emissions in China, we examined whether firms facing climate change would undertake positive actions to adopt more sustainable practices or "go green."

Second, we determined how environmental regulations affect firms' environmental protection behavior. Unlike the voting system in developed countries, the pressure of championship (Li and Zhou, 2005) and supervision of the central government (Piotroski et al., 2015) motivate Chinese local government officials to constrain pollutant emissions to ensure the success of their political careers (He et al., 2020; Liu et al., 2021). We also discovered that environmental regulations enforced by both central and local governments affect the pollutant emissions of firms when

TABLE 12 Climate change and firms’ productivity processes.

	(1)	(2)	(3)	(4)
	Hours of productivity	Hours of productivity	Coal consumption	Coal consumption
<i>Detatem3</i>	−0.047***		−0.096***	
	(0.009)		(0.010)	
<i>Detatem5</i>		−0.040***		−0.026**
		(0.009)		(0.011)
<i>Size</i>	0.113***	0.113***	0.164***	0.164***
	(0.002)	(0.002)	(0.004)	(0.004)
<i>Lev</i>	0.069***	0.069***	−0.116***	−0.116***
	(0.010)	(0.010)	(0.013)	(0.013)
<i>Intangible</i>	−0.298	−0.296	−0.274	−0.274
	(0.204)	(0.204)	(0.232)	(0.232)
<i>ROA</i>	0.080***	0.080***	0.082***	0.082***
	(0.012)	(0.012)	(0.013)	(0.013)
<i>Age</i>	−0.027***	−0.027***	0.015***	0.015***
	(0.004)	(0.004)	(0.005)	(0.005)
<i>SOE</i>	−0.016	−0.017	0.035**	0.035**
	(0.010)	(0.010)	(0.017)	(0.017)
<i>Entry</i>	0.092***	0.092***	−0.023***	−0.023***
	(0.003)	(0.003)	(0.004)	(0.004)
<i>GDP</i>	0.094	0.082	2.582***	2.529***
	(0.076)	(0.076)	(0.126)	(0.124)
<i>Structure</i>	0.355**	0.357**	2.437***	2.393***
	(0.179)	(0.179)	(0.237)	(0.236)
<i>Urban</i>	−0.508*	−0.512*	0.579	0.622
	(0.262)	(0.262)	(0.396)	(0.395)
<i>Inv</i>	0.038	0.039	0.591***	0.581***
	(0.029)	(0.029)	(0.037)	(0.038)
<i>FDI</i>	0.077***	0.078***	0.436***	0.436***
	(0.023)	(0.023)	(0.027)	(0.027)
<i>Intercept</i>	0.335	0.620	−104.585***	−102.841***
	(2.003)	(2.000)	(3.713)	(3.669)
Province FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
<i>N</i>	293,807	293,807	293,807	293,807
Adj- <i>R</i> ²	0.053	0.053	0.161	0.161

*, **, and *** represent the significance of the coefficient at 10, 5, and 1%, respectively; standard error clustered by firm is shown in the parenthesis.

they are confronted with the challenges of addressing climate change.

Finally, we clarified whether environmental considerations and economic goals are complementary or incompatible (Rugman and Verbeke, 1998). We also expanded on the research of He et al. (2020) by investigating which approach to environmental

protection is most effective under the pressure of climate change and environmental regulations. These approaches include direct reduction of pollutive productivity and energy consumption, implementing “end-of-pipe” interventions such as purchasing environmental protection equipment (He et al., 2020) and promoting green innovation (Acemoglu et al., 2011).

TABLE 13 Climate change and firms’ end-of-pipe intervention.

	(1)	(2)	(3)	(4)
	Number of equipment tackling waste gas	Number of equipment tackling waste gas	Capacity of equipment tackling waste gas	Capacity of equipment tackling waste gas
<i>Detatem3</i>	0.027***		0.158***	
	(0.005)		(0.031)	
<i>Detatem5</i>		0.017***		0.123***
		(0.005)		(0.029)
<i>Size</i>	0.093***	0.093***	0.391***	0.391***
	(0.002)	(0.002)	(0.007)	(0.007)
<i>Lev</i>	0.036***	0.036***	0.305***	0.306***
	(0.005)	(0.005)	(0.031)	(0.031)
<i>Intangible</i>	−0.107	−0.108	0.108	0.102
	(0.103)	(0.103)	(0.594)	(0.594)
<i>ROA</i>	0.039***	0.039***	0.121***	0.122***
	(0.006)	(0.006)	(0.035)	(0.035)
<i>Age</i>	0.019***	0.019***	0.006	0.006
	(0.002)	(0.002)	(0.012)	(0.012)
<i>SOE</i>	0.116***	0.116***	0.331***	0.331***
	(0.008)	(0.008)	(0.034)	(0.034)
<i>Entry</i>	0.051***	0.051***	0.236***	0.236***
	(0.002)	(0.002)	(0.009)	(0.009)
<i>GDP</i>	0.078*	0.088*	1.542***	1.588***
	(0.045)	(0.045)	(0.265)	(0.265)
<i>Structure</i>	−0.021	−0.016	−1.143**	−1.140**
	(0.099)	(0.099)	(0.567)	(0.568)
<i>Urban</i>	0.524***	0.520***	−0.442	−0.441
	(0.146)	(0.146)	(0.833)	(0.833)
<i>Inv</i>	−0.101***	−0.100***	−0.386***	−0.388***
	(0.017)	(0.017)	(0.097)	(0.097)
<i>FDI</i>	0.069***	0.069***	0.790***	0.788***
	(0.013)	(0.013)	(0.074)	(0.074)
<i>Intercept</i>	−2.931**	−3.223***	−57.386***	−58.578***
	(1.181)	(1.183)	(7.001)	(7.014)
Province FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
<i>N</i>	293,807	293,807	293,807	293,807
Adj- <i>R</i> ²	0.415	0.415	0.533	0.533

*, **, and *** represent the significance of the coefficient at 10, 5, and 1%, respectively; standard error clustered by firm is shown in the parenthesis.

7.2. Conclusion

Our results revealed that firms in China reduce pollutant emissions because of climate change, an action that is motivated by political pressure. Cross-sectional tests indicated that in areas with “Two control zones” established by the central government

and in areas where local governments enforce more stringent environmental regulations, firms are more effective in reducing pollutant emissions when faced with climate change. Furthermore, firms reduce pollutant emissions by limiting productivity and implementing end-of-pipe interventions. However, there was no evidence to suggest that climate change enhances firms’ green

TABLE 14 Climate change and green innovation.

	(1)	(2)	(3)	(4)
	Green innovation under the classification of OECD	Green innovation under the classification of OECD	Green innovation under the classification of WIPO	Green innovation under the classification of WIPO
<i>Detatem3</i>	0.001		−0.001	
	(0.001)		(0.002)	
<i>Detatem5</i>		−0.001		−0.001
		(0.001)		(0.002)
<i>Size</i>	0.010***	0.010***	0.019***	0.019***
	(0.000)	(0.000)	(0.001)	(0.001)
<i>Lev</i>	−0.002**	−0.002**	−0.004**	−0.004**
	(0.001)	(0.001)	(0.001)	(0.001)
<i>Intangible</i>	−0.061***	−0.061***	−0.132***	−0.132***
	(0.009)	(0.009)	(0.013)	(0.013)
<i>ROA</i>	0.005***	0.005***	0.007***	0.007***
	(0.001)	(0.001)	(0.002)	(0.002)
<i>Age</i>	0.001***	0.001***	0.003***	0.003***
	(0.000)	(0.000)	(0.001)	(0.001)
<i>SOE</i>	0.017***	0.017***	0.034***	0.034***
	(0.002)	(0.002)	(0.003)	(0.003)
<i>Entry</i>	−0.001**	−0.001**	−0.003***	−0.003***
	(0.000)	(0.000)	(0.000)	(0.000)
<i>GDP</i>	−0.001	−0.000	0.016	0.016
	(0.007)	(0.007)	(0.011)	(0.011)
<i>Structure</i>	0.001	0.002	0.049	0.049
	(0.018)	(0.018)	(0.030)	(0.030)
<i>Urban</i>	0.047*	0.046*	−0.010	−0.010
	(0.027)	(0.027)	(0.043)	(0.043)
<i>Inv</i>	−0.001	−0.001	−0.009*	−0.009*
	(0.003)	(0.003)	(0.005)	(0.005)
<i>FDI</i>	0.001	0.001	0.003	0.003
	(0.002)	(0.002)	(0.003)	(0.003)
<i>Intercept</i>	−0.187	−0.203	−0.611*	−0.615*
	(0.199)	(0.199)	(0.326)	(0.327)
Province FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
<i>N</i>	293,807	293,807	293,807	293,807
Adj- <i>R</i> ²	0.026	0.026	0.043	0.043

*, **, and *** represent the significance of the coefficient at 10, 5, and 1%, respectively; standard error clustered by firm is shown in the parenthesis.

innovation. These results indicated that, although firms in China actively decrease pollutant emissions due to political pressure from climate change and environmental regulations, this phenomenon is driven by production factors and investments rather than innovation, which reflects conflicting views on the environment and economy.

This study has two practical implications. First, the government should encourage firms to play an active role in addressing climate change. Environmental regulations are an important factor in internalizing pollution externalities and guiding enterprises to actively reduce their pollutant emissions. In addition, the government should implement a more intensive and accurate

national environmental pollution monitoring system to monitor the pollutant emissions from enterprises in a timely manner and ensure that they take primary responsibility for pollution control. Furthermore, the central government should actively implement measures to eliminate cross-boundary pollution, compensate for the limitations of local governments in implementing environmental regulation policies, and increase punishment for cross-boundary pollution. In addition, the concept of green development should be actively promoted to both firms and the public to reach a consensus on green development in society.

Second, when evaluating the effectiveness of firms' environmental governance and emission reduction efforts, the government should provide greater incentives for innovative approaches to achieving environmental protection goals. In China, firms' environmental protection and pollutant reduction efforts are almost entirely driven by restrictions. Considering that the conflict between environmental protection and economic growth seems to be unavoidable (Nordhaus, 2019), firms tend to prioritize their short-term benefits over long-term benefits (Cohen and Zarowin, 2010; Liu et al., 2021). Additionally, innovation is viewed as risky, requires massive input, and is time consuming (Moshirian et al., 2021). As such, firms choose to invest more in environmental protection equipment instead of engaging in green innovation. The government should incentivize firms to engage in green innovation to create a win-win situation for economic growth and environmental protection.

The government should also promote cooperation between public and private capital in green innovation projects. Moreover, the government can provide appropriate services to help firms overcome challenges that arise during green innovation processes, such as by providing information and knowledge resources.

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.

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Author contributions

ZX: conceptualization, methodology, software, and the writing of the manuscript. CC: substantially revised the article and polished the language of the latest manuscript. LW: wrote part of the manuscript. YM: prepared the original data for key variables and prepared the original draft. All authors contributed to the article and approved the submitted version.

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Conflict of interest

YM was employed by Qingdao Qianwan Container Terminal Co., Ltd.

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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Does ESG performance promote vitality of capital market? Analysis from the perspective of stock liquidity

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Environmental, Social, and Governance (ESG) is changing from a concept to corporate soft power. Can this improve corporate performance in capital markets? There is little literature linking environmental, Social, and Governance performance to stock liquidity. Therefore, It is of urgent theoretical and practical importance to study the impact of environmental, Social, and Governance performance on stock liquidity. Using Chinese A-share listed companies from 2015 to 2020 as a sample to empirically examine the impact of environmental, Social, and Governance performance on stock liquidity and its mechanism. We find that environmental, Social, and Governance performance has a significant positive impact on listed companies' stock liquidity. This conclusion was validated after conducting a series of robustness tests. Mechanism analysis shows that environmental, Social, and Governance performance can promote stock liquidity by reducing agency costs, increasing the proportion of foreign ownership, and improving corporate reputation. The heterogeneity analysis shows that environmental, Social, and Governance performance in state-owned enterprises, heavily polluting enterprises, and enterprises in areas with low degrees of marketisation has a more significant positive promoting effect on stock liquidity. This study expands the research on environmental, Social, and Governance performance and has implications for promoting the development of environmental, Social, and Governance practices.

KEYWORDS

ESG performance, stock liquidity, capital market vitality, agency costs, foreign ownership, corporate reputation

1 Introduction

New changes in social contradictions can lead to changes in a country's developmental philosophy. Currently, the major dilemma in China is the conflict between people's growing desire for better living conditions and their uneven and insufficient development. A report by the 20th National Congress of the Communist Party of China indicated that China's economy will shift from a stage of high growth to a stage of high-quality development. We should deeply implement the new development concept of "innovation, coordination, green, openness, and sharing" and comply with the development trend of sustainability. The realization of sustainable development goals at the national level requires many micro-entities to actively assume social responsibilities, reshape their business philosophy, and

realise a transformation from maximising self-interest to maximising social values. Distinguished from traditional financial indicators, Environmental, Social, and Governance (ESG) is a non-financial enterprise evaluation system that focuses on the environment, society, and governance. This is an important indicator for measuring enterprises sustainable development ability and determining whether they have a sufficient sense of social responsibility. Driven by such changes in social contradictions and policies, the practice of ESG's new development concept isn't only a hot issue for the government, academia, and the public but also a necessary path for microeconomic entities to achieve sustainable development.

In 2004, the United Nations Environment Program formally put forward the concept of ESG for the first time, requiring enterprises to give full consideration to environmental protection, social responsibility, and corporate governance in the process of operation and development and setting a three-tier bottom line to quantify non-financial risks: environmental, social, and governance. In 2018, China Securities Regulatory Commission revised the "Code of Governance for Listed Companies," which stipulates that listed companies shall disclose information related to environmental protection, social responsibility fulfilment, and corporate governance following laws and regulations and requirements of relevant departments. In this context, the preference for listed Chinese companies to practice the ESG concept continues to increase. According to the 2021 ESG Performance Analysis Report of A-share Listed Companies released by Syntao, a Chinese ESG performance agency, the number of ESG disclosure reports issued by A-share listed companies increased from 371 in 2009 to 1,125 in 2021. Objectively, the ESG concept will inevitably impact enterprise development and, to a certain extent, be mapped to capital market activities. As a lifeline of the capital market, stock liquidity largely reflects the price discovery function and resource allocation efficiency of the capital market and is often closely associated with market recognition (Amihud and Mendelson, 1988). Thus, a company's business philosophy and core values are reflected, to a certain extent, by capital market liquidity, and the ESG philosophy is no exception.

However, few studies have accurately linked ESG performance and stock liquidity, and the direction and mechanism of their influence can only be inferred from other relevant literature. Good ESG performance can improve information transparency, alleviate information asymmetry, reduce agency conflicts, and thus reduce the costs of equity (El et al., 2011) and debt (Goss and Roberts, 2011). In addition, ESG can restrain manager misconduct (He et al., 2022), reduce systemic and special risks (Cerqueti et al., 2021), and play a positive role in corporate governance and risk management. More importantly, most studies find that ESG can significantly improve enterprise performance and long-term value (Friede et al., 2015; Li et al., 2020). From this perspective, ESG promotes the high-quality development of enterprises (Li et al., 2021) and generates positive feedback in the capital market, such as improving stock liquidity. Contrastingly, some scholars found that ESG is negatively correlated with corporate value (Brammer and Pavelin, 2006), and compulsory disclosure of corporate social responsibility increases costs (Chen et al., 2018) thereby leading to ineffective use of corporate resources (Alexander and Buchholz,

1978). To satisfy their original intention of self-interest, managers may take advantage of the reputational insurance effect of social responsibility activities to engage in high-risk activities (Barnea and Rubin, 2010), thus bringing uncertainty to enterprise operations. Therefore, enterprises with good ESG performance have lower corporate value (Sassen et al., 2016). Some scholars believe there is no correlation between ESG and enterprise value (Atan et al., 2018). Based on these studies, we can infer that ESG may not improve the active performance of enterprises in capital markets.

In summary, the inferences obtained from the existing literature on the relationship between ESG performance and stock liquidity haven't yet been agreed upon and require further in-depth research. To evaluate the consequences of ESG and its role in carrying out sustainable development activities, this study focuses on exploring the impact of ESG performance on stock liquidity and its mechanism of action. It considers enterprise ESG performance as the core explanatory variable to explore whether listed companies stock liquidity responds positively to ESG performance. At the same time, this study also demonstrates the potential mechanism of action from three perspectives: agency costs, foreign stock ownership, and corporate reputation. Further, the sample enterprises are subdivided according to certain characteristic variables to analyse the heterogeneous characteristics of the impact of ESG performance on stock liquidity. This study also explores the influence, channel mechanisms, and heterogeneity of the influence between ESG and stock liquidity to provide new evidence for understanding ESG performance and capital market liquidity of Chinese listed companies.

The main contributions of this paper are in the following three areas: First, The existing literature focuses on the impact of ESG on firm value (Alareeni and Hamdan, 2020), financial risk (Shakil, 2021), innovation capacity (Tan and Zhu, 2022) and the cost of debt (Eliwa et al., 2021), few studies have focused on the role of ESG performance in enhancing capital market vitality. This paper examines the impact of corporate ESG performance from the perspective of stock liquidity, expands the boundaries of the economic consequences of ESG performance, reveals the positive effects of ESG on corporate capital market performance, and provides empirical support for promoting ESG investment, actively fulfilling ESG responsibilities and implementing the concept of sustainable development. Second, this paper extends the study on the factors influencing stock liquidity by proposing a new influencing factor, ESG performance, which combines the framework of green transformation-driven enterprises under the ESG system with the enhancement of enterprise stock activation in the capital market. Third, we examine the heterogeneity of ESG performance on stock liquidity from three perspectives: enterprise, industry, and market, and explore the intrinsic mechanism of ESG performance to promote capital market dynamics through the paths of agency costs, foreign ownership, and corporate reputation, which not only enriches the relevant literature academically, but also provides new research ideas and perspectives for subsequent related studies. Fourth, the findings of this paper provide a theoretical basis for enterprises to improve their capital market performance by enhancing ESG performance, which is an important reference value for investors' decision making and has implications for the government to improve the construction of China's ESG disclosure system.

2 Theoretical analysis and hypothesis development

Stock liquidity¹ mainly reflects the ability to liquidate assets and the degree of stock market activity and is a central element in the efficient functioning of capital markets (Amihud and Mendelson, 1986; Du et al., 2017). Stock liquidity isn't only related to asset prices but also has an important impact on capital structure (Lipson and Mortal, 2009), investment decisions (Benlemlih and Bitar, 2018), and R&D innovation (Fang et al., 2014), among others. Therefore, stock liquidity has become an important topic in capital market microstructure research. In the existing literature, the factors influencing stock liquidity have been explored in-depth and can be broadly summarized at the macro level and micro level. At the macro level, some scholars find that factors, such as capital market opening (Bekaert et al., 2002), monetary policy (Chordia et al., 2005), and capital market system reforms (Zhao et al., 2020) can have an impact on stock liquidity. At the micro level, studies have analyzed the impact of investor sentiment (Liu, 2015), institutional investor holdings (Dang et al., 2018), and market maker system (Grossman and Miller, 1988) on stock liquidity.

Stock liquidity is the basis of capital market functions such as price discovery, information flow, and resource allocation (Amihud and Mendelson, 1988), and reflects the quality, efficiency, and vitality of enterprises to a large extent (Benlemlih and Bitar, 2018). The ESG concept is an important tool to improve the quality and efficiency of the real economy through the high-quality development of micro-entities, reflecting the transformation of the business philosophy from shareholder value maximisation to stakeholder value maximisation. This new development concept will be reflected in the stock liquidity of the capital market. ESG performance consists of three dimensions: environmental, social, and corporate governance. First, through multidimensional non-financial information disclosure, enterprises can effectively alleviate information asymmetry, help investors understand the actual situation of enterprises from multiple perspectives, and bring into play the monitoring role of all parties (including intermediaries and stakeholders) in the capital market, thus reducing agency costs. Second, under the uncertainty of the external environment, ESG performance is a competitive advantage for enterprises and an important dimension for measuring the sustainable development performance and long-term investment value of enterprises; this is an important basis for investor's investment decisions and helps attract the attention of institutional investors, including foreign investors, the increased investment attention will lead to higher foreign ownership. Finally, good ESG performance connotes good environmental, social, and

corporate governance performance, which embodies creating diversified integrated value and safeguarding stakeholders, helping companies establish a good corporate image in the capital market, improving corporate reputation, and helping companies to achieve long-term value and sustainable development. From the above, the changes brought by ESG enhance information transparency (Ellili, 2022), foreign ownership (Yu and Zheng, 2020), corporate reputation (Maaloul et al., 2021), and other factors required for trading in the capital market, which can have a significant impact on stock liquidity. Therefore, this study explores the impact of corporate ESG performance on stock liquidity and its mechanism of action using the three main paths mentioned above.

Information asymmetry is a key factor affecting stock liquidity. The more serious the adverse selection and moral hazard problems caused by information asymmetry, the higher the agency cost and the worse the stock liquidity will be (Bhide, 1993). According to the principal-agent theory, there is serious information asymmetry between management and investors, and it is entirely possible for management to take advantage of information to make business decisions that are unfavourable to investors, thus generating higher agency costs. Good ESG performance enhances stock liquidity by improving information efficiency and reducing agency costs. First, the disclosure of non-financial information is a useful supplement to the disclosure of financial information and helps improve information transparency. ESG discloses non-financial information that can alleviate information asymmetry and reduce agency costs (Siew et al., 2016). Second, good ESG performance implies that the company has a sound corporate governance mechanism, can strictly comply with relevant laws and regulations, has lower operational risks, and has a higher sense of social responsibility, thereby reducing investment risks. Third, companies with good ESG performance receive more media attention, and their management faces stronger external monitoring pressure, which can also motivate companies to operate prudently and compliantly while reducing agency costs and curbing short-selling, inefficient investments, and on-the-job consumption.

ESG performance can attract foreign capital inflows and increase foreign ownership, thereby improving stock liquidity. As the market value of listed companies is closely related to ESG performance, foreign institutions take the ESG index as an important investment consideration factor (Cheng et al., 2015) to measure whether listed companies have sufficient ESG risk control ability and sustainable profitability (Stelner et al., 2015). According to the stakeholder theory, social responsibility in a broad sense has both economic and moral dimensions (Clarkson, 1995). A good evaluation of corporate social responsibility means that enterprises can effectively coordinate these two kinds of different responsibilities and maintain the balance between them. Social responsibility, an important aspect of ESG, can significantly affect institutional investor's investment decisions. Mahoney and Roberts (2007) finds a significant positive correlation between CSR performance and the number of institutional investors. Furthermore, foreign ownership helps optimise the shareholding structure, diversify risks, and reduce the cost of capital (Bekaert and Harvey, 2000). Additionally, foreign investors have a higher sense of rights and participation, which helps improve the level of corporate governance

¹ Although the findings on the consequences of stock liquidity are not uniform (Amihud and Mendelson, 1988) (Benlemlih and Bitar, 2018), however, a large number of studies targeting the Chinese capital market have shown that stock liquidity has a positive effect on the efficiency of the capital market (Du et al., 2017) (Zhao et al., 2020). In practice, a series of major reforms by the Chinese government targeting the capital market, such as the equity division reform and the registration system reform, is conducive to promoting stock liquidity. Theoretically, there are differences in the mechanisms of stock liquidity due to the nature of property rights, institutional environment, and other aspects.

TABLE 1 Definitions of variables.

Symbol	Variable	Definition
Liquidity	Stock liquidity	Opposite of Amihud illiquidity indicator
ESG	ESG comprehensive performance	ESG disclosure score in Bloomberg
ENV	Environmental performance	Environmental disclosure score in Bloomberg
SOC	Social performance	Social disclosure score in Bloomberg
GOV	Corporate governance	Governance disclosure score in Bloomberg
Lev	Total liabilities ratio	Total liabilities/total assets
ROA	Return on total assets ratio	Return/total assets
Size	Firm size	Natural logarithm of number of employees
Age	Firm age	Natural logarithm of years from the firm establishment
Indep	Proportion of independent directors	Number of independent directors/number of directors
Dual	Dual position	CEO and Board director is the same person equals to one, otherwise zero
BM	Book to market ratio	Total assets/total market value
Top1	shareholding ratio of the largest shareholder	Percentage of shares held by the largest shareholder
CRT3	Stock Return Volatility	Natural logarithm of annual standard deviation of monthly returns

and operational efficiency of enterprises. Moreover, foreign investors, as investment subjects with strong professionalism, tend to be the focus of the market, and their investment behaviour can influence the investment behaviour of other investors, helping attract more capital, forming a herding effect, generating co-investment behaviour, and promoting an increase in trading volume. In addition, some scholars have found that foreign ownership may positively affect stock liquidity through various channels such as trading (Ding et al., 2017), competition channels (Gou and Zheng, 2021), and information channels (Glosten and Milgrom, 1985).

ESG performance contributes to a company's reputation, enhances its market position, and creates a unique competitive advantage, thereby improving its stock liquidity. First, regarding certification effects, investors lack sufficient quality information because of limited access to information. Reputation is gradually accumulated by a firm through its efforts and costs over time and constitutes a kind of guarantee and collateral for the firm (Tadelis, 1999), thus influencing the investment decisions of external investors. Good ESG performance improves a company's reputation in the capital market. Second, from the information perspective, companies that focus on their reputation send positive signals to the market and attract external attention by increasing the quantity and quality of information disclosure, thus maintaining a high reputation and a good image and gaining investor's trust and support, which also helps reduce information asymmetry between companies and investors and promotes trading behaviour. Third, corporate reputation is an evaluation made by stakeholders based on how well their expectations are met (Haleblian et al., 2017). A good social reputation is a fundamental resource for creating business value for firms. Enterprises with good reputations have unique competitive advantages in the market (Roberts and Dowling, 2002), which can enhance product market competitiveness

(Brammer and Pavelin, 2004), ease financing constraints, lower the cost of capital, and thus reduce business risks (Dowling, 2006). A good reputation is also a positive signal in the market, which can stabilise market expectations and create a positive "exposure effect" (Zhao et al., 2020), attracting more investors to participate and increasing the vitality of the capital market. In addition, enterprises high ESG performance can ensure government support and a relaxed external environment for their development (Niessen and Ruenzi, 2010). More importantly, the ESG practices of enterprises can gain public recognition, which can reduce consumers' price sensitivity (Flammer, 2015) and help enterprises form brand effects, enhance their potential and lasting competitive advantages, and improve stock liquidity. Based on this analysis, this study proposes the following core research hypothesis.

Hypothesis. 1 Other things being equal, ESG performance will significantly increase the level of stock liquidity.

3 Data and empirical design

3.1 Data

This paper selects the data of Chinese A-share listed companies from 2015 to 2020 as the initial research sample and makes the following treatment: 1) Excluding the special treatment firms (ST and PT firms); 2) Excluding financial firms; 3) Excluding the sample with abnormal or missing ESG and other key data. To eliminate the influence of extreme values, all continuous variables are winsorized at the 1% and 99% levels. Finally, we obtain a total of 5,944 observations. The financial data of listed companies in this paper are obtained from CSMAR (China Stock Market and Accounting Research Database), and the ESG score data are obtained from Bloomberg database.

TABLE 2 Descriptive statistical results of variables.

Variable	N	Mean	Std	Median	Min	Max
Liquidity	5,944	-2.6398	3.5327	-1.5754	-25.1990	-0.1624
ESG	5,944	21.6832	7.1482	20.2479	10.7438	44.6281
E	5,265	11.8714	8.7203	9.3023	2.0833	43.4109
S	5,927	24.2969	9.8284	22.8070	7.0175	56.1404
G	5,944	45.3771	5.1066	44.6429	33.9286	58.9286
Lev	5,944	0.4574	0.1904	0.4640	0.0752	0.8652
ROA	5,944	0.0462	0.0622	0.0379	-0.1661	0.2404
Size	5,944	8.5050	1.2266	8.4714	5.7071	11.8123
Age	5,944	2.9735	0.2825	2.9957	2.1972	3.4657
Indep	5,944	0.3758	0.0549	0.3636	0.3125	0.5714
Dual	5,944	0.2143	0.4104	0.0000	0.0000	1.0000
BM	5,944	1.3050	1.3740	0.8322	0.1005	7.7360
Top1	5,944	0.3550	0.1544	0.3375	0.0880	0.7526
CRT3	5,944	-2.2551	0.4668	-2.2532	-3.3100	-1.1173

3.2 Variables definition

3.2.1 Dependent variable

Stock liquidity (Liquidity). This paper draws on Amihud and Mendelson's (Amihud and Mendelson, 1988) research method to find the stock illiquidity indicator (ILLIQ) by Eq. 1.

$$ILLIQ_{i,t} = \frac{1}{D_{i,t}} \sum_{d=1}^{D_{i,t}} \left(\frac{|r_{i,t,d}|}{V_{i,t,d}} \right) \times 100 \quad (1)$$

Where, $D_{i,t}$ represents the number of trading days of enterprise i in t year, $|r_{i,t,d}|$ represents the return rate of enterprise i considering the reinvestment of cash dividends on the d trading day of t year; $V_{i,t,d}$ represents the transaction amount of enterprise i on the d trading day of t year; Therefore, $|r_{i,t,d}|/V_{i,t,d}$ represents the change in the return rate of enterprise i caused by the transaction amount per million on the d trading day of t year. After taking the mean of the sum and multiplying it by 100, it is the illiquidity index. The larger the value of ILLIQ is, the greater the impact of unit transaction amount on the stock, the higher the transaction cost for investors, and the worse the stock liquidity. To more intuitively reflect the relationship between ESG performance and stock liquidity, this paper takes the opposite of the illiquidity indicator to obtain the liquidity indicator shown in Eq. 2, whose larger value represents the stronger liquidity of the corresponding stock.

$$Liquidity = -ILLIQ \quad (2)$$

3.2.2 Independent variables

Corporate ESG performance (ESG). At present, academics mainly use the construction of multi-dimensional index systems or use third-party institutions to evaluate and assign scores to measure the ESG performance of enterprises. Since self-constructed indicators are highly subjective and do not

correspond to the actual basic situation in China, we followed Ge et al. (2022) cites the ESG score of listed companies provided by Bloomberg Consulting as a measure of corporate ESG performance, which can be subdivided into three types: environment (ENV), social responsibility (SOC), and corporate governance (GOV), and a higher ESG score means a better ESG performance. In the subsequent robustness tests, the corporate ESG scores provided by Hexun are used as proxy variables in this paper.

3.2.3 Control variables

To overcome omitted variable bias, this paper selects total liabilities ratio (Lev), return on total assets ratio (ROA), firm size (Size), firm age (Age), the proportion of independent directors (Indep), duality of the chairman and CEO (Dual), book-to-market ratio (BM), shareholding ratio of the largest shareholder (Top1), and stock return volatility (CRT3) as control variables. The specific definitions of each variable can be found in Table 1.

3.3 Research method

To test the relationship between ESG performance and stock liquidity, we followed Ma et al. (2022) to construct the following baseline regression model:

$$Liquidity_{y,it} = \alpha_0 + \alpha_1 ESG_{i,t-1} + \sum \alpha Controls + \sum Year + \sum Ind + \varepsilon_{it} \quad (3)$$

In the above model, the explanatory variable in Eq. 3 is stock liquidity (Liquidity), the explanatory variable is corporate ESG performance (ESG), and Controls is the aforementioned control variable, ε_{it} is the model random error term. In order to improve the reliability of the regression results, this paper also does the following basic treatments: first, considering that a certain time lag is required for the impact of corporate ESG scores on stock liquidity in the capital market, this paper treats the explanatory variables with a one-period lag, which takes into account the time-consuming transmission between variables in practice and can alleviate the endogeneity problem between variables to a certain extent; second, this paper controls the time (Year) and industry (Ind) dummy variables to absorb fixed effects as much as possible. Third, to make the statistical inference results more robust, this paper uses robust standard errors to estimate Eq. 3.

4 Empirical results and analysis

4.1 Descriptive statistics

Table 2 presents the descriptive statistics of the main variables in this study. The results show that the mean value of stock liquidity (Liquidity) is -2.6398, and the minimum and maximum values are -25.1990 and -0.1624, respectively, indicating that investors pay different levels of attention to different stocks and that the differences are contrasting. The maximum ESG score (ESG) of listed companies is 44.6281, and the minimum is 10.7438,

TABLE 3 Baseline regression results.

Variable	(1)	(2)	(3)	(4)
	Liquidity	Liquidity	Liquidity	Liquidity
L.ESG	0.0183*** (4.0548)			
L.E		0.0149*** (4.2933)		
L.S			0.0101*** (3.2001)	
L.G				0.0222*** (3.3830)
Lev	−0.0338 (−0.1331)	−0.1279 (−0.5004)	−0.0116 (−0.0451)	−0.0729 (−0.2853)
ROA	7.8581*** (10.6495)	7.9790*** (9.6487)	7.8202*** (10.6138)	7.8665*** (10.6331)
Size	0.8278*** (22.6617)	0.8917*** (23.7344)	0.8419*** (23.9860)	0.8387*** (23.3503)
Age	−0.2019 (−1.5114)	−0.1753 (−1.2429)	−0.1744 (−1.3054)	−0.2298* (−1.7057)
Indep	0.4570 (0.8859)	0.6474 (1.1938)	0.5844 (1.1381)	0.4476 (0.8678)
Dual	0.0023 (0.0296)	0.0443 (0.5385)	−0.0001 (−0.0013)	0.0038 (0.0470)
BM	−0.1558*** (−4.3550)	−0.1591*** (−5.2278)	−0.1527*** (−4.2763)	−0.1511*** (−4.2825)
Top1	−1.9137*** (−8.8002)	−1.7489*** (−7.6089)	−1.8722*** (−8.6163)	−1.9496*** (−8.9820)
CRT3	0.4326*** (3.6512)	0.4763*** (4.2194)	0.4284*** (3.6022)	0.4447*** (3.7633)
Constant	−6.7556*** (−10.1370)	−7.4475*** (−10.7599)	−7.1749*** (−10.8238)	−7.3293*** (−10.7035)
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
N	4,821	4,229	4,808	4,821
r2_a	0.3097	0.3307	0.3084	0.3094

Note: *, **, *** indicate a notable level of significance at respectively 10%, 5%, and 1%, and the values in parentheses are robust standard errors.

indicating a significant difference in commitment to social responsibility among different companies. Except for enterprise size (Size) and book-to-market ratio (BM), the standard deviations of all control variables are less than one, and the fluctuations are marginal, indicating that the data are relatively stable.

4.2 Baseline regression results

Table 3 presents the results of the baseline regression analysis of corporate ESG performance and stock liquidity. The regression results in Column (1) of Table 3 show that the estimated coefficient of the regression of the corporate ESG performance

TABLE 4 Matched-sample balance test.

Variable	Unmatched	Mean		%Bias	t-test	
	Matched	Treated	Control		t	p > t
Lev	U	0.4875	0.4278	31.8	12.25	0.000
	M	0.4861	0.4942	−4.3	−1.63	0.103
ROA	U	0.0459	0.0466	−1.1	−0.42	0.677
	M	0.0461	0.0456	−0.9	0.35	0.726
Size	U	8.8573	8.1586	59.4	22.90	0.000
	M	8.8400	8.7991	3.5	1.32	0.187
Age	U	3.0174	2.9305	31.2	12.00	0.000
	M	3.0166	3.0278	−4.0	−1.64	0.102
Indep	U	0.3768	0.3749	3.3	1.28	0.202
	M	0.3765	0.3759	1.2	0.44	0.662
Dual	U	0.1720	0.2559	−20.6	−7.92	0.000
	M	0.1731	0.1757	−0.6	−0.26	0.796
BM	U	1.6018	1.0132	43.8	16.91	0.000
	M	1.5626	1.6236	−4.5	−1.45	0.148
Top1	U	0.3722	0.3381	22.2	8.54	0.000
	M	0.3713	0.3699	0.9	0.35	0.726
CRT3	U	−2.3212	−2.1901	−28.4	−10.93	0.000
	M	−2.3178	−2.3091	−1.9	−0.72	0.469

variable (ESG) is significantly positive at the 1% level. In terms of economic significance, if a listed company's ESG performance improves by one notch, it can lead to an increase in stock liquidity (Liquidity) by 0.0183. Thus, it can be seen that the better the ESG performance of a company, the better the stock liquidity, and the hypothesis of this study is verified. The results support the findings of the literature such as [Velte \(2017\)](#); [Li et al. \(2018\)](#), and [Miralles-Quirós et al. \(2018\)](#) that corporate ESG helps companies to increase their value and form positive feedback in the capital market, reflecting the value creation effect of ESG practices. From the results of the control variables, the coefficient of return on total assets ratio (ROA) and stock liquidity (Liquidity) is significantly positive, indicating that firms with good profitability are more likely to be favored by investors and promote stock liquidity. Firm size (Size) is significantly and positively correlated with stock liquidity because small firms are less likely to receive market attention and have high implicit transaction costs, thus stock liquidity is correspondingly lower. The coefficient between book to market ratio (BM) and stock liquidity is significantly negative. Book to market ratio represents the risk of financial distress faced by companies, and companies with high book to market ratios are in a more fragile financial position, vulnerable to financial crises and have lower stock security, hence lower stock liquidity. The shareholding ratio of the first largest shareholder (TOP1) is significantly and negatively related to stock liquidity. A larger

shareholding ratio of the first largest shareholder means higher concentration of equity, higher information asymmetry, lower information content of stock price, and higher agency costs, thus making stock liquidity lower. The higher the stock return volatility, the higher the stock liquidity, consistent with the existing literature ([Lang et al., 2012](#)).

Columns (2) to (4) in [Table 3](#) show the regression results of the corporate environmental performance variable (ENV), corporate social performance variable (SOC), and corporate governance performance variable (GOV) on stock liquidity for corporate ESG performance. As can be seen from the regression results in Column (2) of [Table 3](#), the estimated coefficient of the regression of ENV is significantly positive at the 1% level, indicating that the better the corporate environmental performance, the better the stock liquidity. The regression results in Column (3) of [Table 3](#) show that the estimated coefficient of the regression of SOC is significantly positive at the 1% level, indicating that the better the corporate social responsibility performance, the better the stock liquidity. The results in column (4) of [Table 3](#) show that the estimated coefficient of the regression of GOV is significantly positive at the 1% level, indicating that an improvement in corporate governance is beneficial to stock liquidity. In summary, a company's ESG performance affects its performance in the capital market, and good ESG performance contributes to improving stock liquidity.

TABLE 5 Robustness checks.

Variable	(1)	(2)	(3)	(4)
	Zeros	Liquidity	Liquidity	Liquidity
L.ESG	0.0002*** (4.1671)		0.0329*** (4.4521)	0.0183*** (3.7497)
L.ESG2		0.0105*** (5.2235)		
Lev	0.0097*** (3.6538)	0.0640 (0.2503)	−0.0424 (−0.0804)	0.1635 (0.5848)
ROA	0.0964*** (16.2159)	7.3761*** (9.7730)	3.9768*** (3.4925)	8.0532*** (9.9970)
Size	0.0014*** (3.8402)	0.8415*** (24.7058)	1.0380*** (5.2941)	0.8280*** (20.8364)
Age	0.0023* (1.8207)	−0.1902 (−1.4054)	3.8018*** (3.4642)	−0.2656** (−1.9738)
Indep	0.0037 (0.5198)	0.4932 (0.9548)	−0.6946 (−0.8025)	0.5424 (0.9798)
Dual	0.0012 (1.5051)	−0.0102 (−0.1280)	−0.0921 (−0.7574)	−0.0558 (−0.6558)
BM	−0.0076*** (−15.8052)	−0.1424*** (−4.0676)	−0.5000*** (−6.2781)	−0.1985*** (−4.3840)
Top1	0.0040 (1.5810)	−1.8672*** (−8.6352)	−2.3169 (−1.5486)	−1.9395*** (−8.2876)
CRT3	0.0229*** (19.8182)	0.4614*** (3.9088)	0.0921 (0.7733)	0.3930*** (3.0297)
Constant	−0.0075 (−1.1725)	−7.0667*** (−10.6075)	−21.0527*** (−4.8782)	−6.4725*** (−9.4095)
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
N	4,821	4,820	4,821	4,240
r2_a	0.3764	0.3112	0.2865	0.3104

Note: *, **, *** indicate a notable level of significance at respectively 10%, 5%, and 1%, and the values in parentheses are robust standard errors.

4.3 Robustness checks

The baseline regression results suggest that the better a firm's ESG performance is, the higher its stock liquidity. To test the robustness of the regression results, we conducted the following robustness tests.

4.3.1 Alternative measurement for liquidity

To test the robustness of the baseline regression results, this study refers to Lesmond et al. (1999) and estimates the number of

days with zero stock returns (zeros) using Eq. 4, which is used again as a liquidity proxy for the regression analysis, where $ZD_{i,t}$ denotes the number of trading days in which stock i has a zero return in period t and $D_{i,t}$ denotes the number of trading days in year t for stock i . The larger the value of Zeros, the more liquid the stock. The regression results after replacing the liquidity measure are shown in Column (1) of Table 5, which shows that the coefficient between corporate ESG performance and stock liquidity is significantly positive, indicating that the better the corporate ESG performance, the higher the stock liquidity.

TABLE 6 2SLS regression.

Variable	(1)	(2)
	ESG	Liquidity
ESG_IV	0.2678*** (7.4644)	
L.ESG		0.1519*** (2.9719)
Lev	−0.2228 (−0.3806)	0.0412 (0.1553)
ROA	3.9954*** (2.9043)	7.5723*** (10.0649)
Size	1.9785*** (22.6730)	0.5816*** (5.8648)
Age	2.4462*** (8.2599)	−0.5523*** (−2.9383)
Indep	3.5845** (2.3757)	0.0265 (0.0459)
Dual	−0.7398*** (−3.7816)	0.1042 (1.1675)
BM	0.5692*** (5.7114)	−0.2365*** (−4.7031)
Top1	1.7079*** (2.8098)	−2.1893*** (−8.3768)
CRT3	0.1191 (0.5180)	0.4067*** (3.3592)
Constant	−7.1731*** (−5.3636)	−6.7806*** (−9.7664)
Year	Yes	Yes
Industry	Yes	Yes
N	5,944	4,877
r2_a	0.2589	0.2096

Note: *, **, *** indicate a notable level of significance at respectively 10%, 5%, and 1%, and the values in parentheses are robust standard errors.

$$Zeros_{i,t} = -\frac{ZD_{i,t}}{D_{i,t}}$$

(4)

4.3.2 Alternative measurement for ESG performance

Given that corporate ESG performance is not derived from objective information such as corporate financial statements and that the fairness of index compilation by a single institution may be controversial, we use corporate ESG performance data published by Hexun (L.ESG2). The regression results are shown in Column (2) of

Table 5. The results show that the regression coefficient of ESG performance and stock liquidity is 0.0105 and positively correlated at the 1% level, which indicates that the findings of this study are robust.

4.3.3 Controlling for individual fixed effects

Although the previous analysis in this study controlled for industry and annual fixed effects as unobservable firm-level factors may affect both ESG performance and stock liquidity, we controlled for individual fixed effects at the firm level and regressed again. The regression results are shown in Column (3) of Table 5.

The results show that ESG performance remains significantly and positively correlated with stock liquidity, which is consistent with the previous results.

4.3.4 Sample selection bias

A company with good ESG performance may differ from other companies and have unique corporate characteristics in terms of financial level and industry characteristics. To address sample selection bias, this study was validated by propensity score matching (PSM). The test steps were as follows: first, the median ESG performance was used as the threshold to construct the experimental and control groups, and the control variables were used as covariates in the logit regression to calculate the propensity score value; then, the matched samples were paired according to the principle of nearest neighbour matching (1:4) based on the propensity score value; and finally, the matched samples were subjected to regression analysis. The balance test of the matched samples is shown in Table 4, which shows that the standardised deviations of all variables after matching are less than 5%, and the characteristic variables of the matched and control samples aren't significantly different at the 10% level; thus, the parallel hypothesis is satisfied and the matching results are good. The matched regression results are shown in column (4) of Table 5, which shows that the regression coefficients of ESG performance and stock liquidity are positively correlated at the 1% level, indicating that ESG performance still contributes significantly to stock liquidity after controlling for the endogeneity problem arising from sample selection bias.

4.3.5 Instrumental variables method

A country's institutions and culture have a significant impact on companies' environmental protection, social responsibility fulfilment, and corporate governance. Traditional culture and historical values are important determinants of a company's ESG performance. In China's 5,000-year history, the 2,000-year-old Confucian culture is one of the most influential traditional cultures; it has had a significant impact on the formation of Chinese values and has long been used as a moral standard for individuals and organisations. The central ideas of "benevolence," "righteousness," "sincerity," and "love" advocated by Confucianism are highly compatible with ESG philosophy, that is, enterprises should be responsible for the environment, society, and stakeholders. Therefore, the strength of the Confucian culture in the region where the firm is located has an impact on ESG performance and is not related to stock liquidity. The selection of the intensity of Confucian culture in the region where the firm is located as an instrumental variable meets the requirement of being correlated with endogenous variables and independent of the dependent variable. Since the academy is an important place for spreading Confucianism and since the Tang Dynasty, all state and county schools have set up Confucian temples, so to better address the endogeneity issue, we followed He et al. (2022) to use the number of Confucian temples within a 50 km radius of the firm's location to measure the intensity of Confucian culture and use it as an instrumental variable for the firm's ESG performance (ESG_IV) in a two-stage least squares regression, the results of which are shown in columns (1) and (2) of Table 6. Column (1) shows the regression results for the first stage, where the coefficients of the instrumental variable (ESG_IV) and ESG performance are

significantly positive at the 1% level, indicating that the intensity of Confucian culture in the region is significantly and positively related to firms' ESG performance. The p -value of the under-identification test (Kleibergen-Paap rk LM) statistic is 0, indicating that there is no problem with the under-identification of instrumental variables, while the value of the weak instrumental variable test (Kleibergen-Paap rk Wald F) statistic is 44.247, much larger than the 10% level threshold (16.38), indicating that there is no problem of weak instrumental variables. Column (2) shows the results of the second stage of the regression, where the coefficient of ESG performance is 0.1519, which is significantly positive at the 1% level and consistent with the baseline regression results. Therefore, the conclusion that ESG performance promotes corporate stock liquidity still holds after controlling for endogeneity using instrumental variables.

5 Further research

5.1 The impact of corporate ESG performance on stock liquidity: Based on the ownership

Ownership is the most typical corporate characteristic in the Chinese capital market context, and there are certain differences between state-owned and non-state-owned enterprises in terms of business objectives, social responsibility commitment, and political affiliation. On the one hand, as an important pillar of national economic development, state-owned enterprises have the dual mission of achieving economic development and fulfilling social responsibility and should take the initiative to increase ESG investment, actively assume social responsibility, and play an exemplary role in the construction of the ESG system. On the other hand, due to the advantage of access to policy resources and market financing, state-owned enterprises are better able to achieve a balance between economic and social benefits in the performance of ESG practices. This can ensure ESG sustainability and create the maximum value of ESG practices to enhance enterprise's performance in the capital market. Therefore, this paper argues that the effect of the ESG performance of state-owned enterprises on stock liquidity will be stronger than non-state-owned enterprises. To verify whether the impact of corporate ESG performance on stock liquidity differs by ownership type, this study adds ownership (L.SOE) and the interaction term between ownership and ESG performance (L.ESG×L.SOE) to Eq. 1. According to Column {1} of Table 7, the coefficient of the interaction term between ESG performance and ownership is 0.0180 and is significant at the 5% level. Therefore, the positive contribution of corporate ESG performance to stock liquidity is more significant in state-owned enterprises.

5.2 The impact of corporate ESG performance on stock liquidity: Based on the nature of corporate pollution

Enterprises with different pollution characteristics are subject to different environmental regulatory pressures. This paper followed

TABLE 7 Further analysis.

Variable	(1)	(2)	(3)
	Liquidity	Liquidity	Liquidity
L.ESG	0.0082 (1.3232)	0.0093* (1.9098)	0.0557** (2.4599)
L.SOE	-0.2993 (-1.5162)		
L.ESG×L.SOE	0.0180** (2.3077)		
L.IFHP		-0.8683*** (-3.6101)	
L.ESG×L.IFHP		0.0286*** (3.2361)	
L.MDI			0.0877 (1.3852)
L.ESG×L.MDI			-0.0042* (-1.7093)
Lev	0.0151 (0.0598)	0.0327 (0.1286)	-0.0432 (-0.1715)
ROA	7.9160*** (10.7323)	7.8655*** (10.7240)	7.8012*** (10.6764)
Size	0.8286*** (22.7409)	0.8212*** (22.6608)	0.8299*** (22.9704)
Age	-0.2044 (-1.4534)	-0.2065 (-1.5594)	-0.1995 (-1.4792)
Indep	0.3998 (0.7857)	0.3137 (0.6166)	0.4856 (0.9570)
Dual	0.0208 (0.2597)	-0.0118 (-0.1497)	0.0023 (0.0295)
BM	-0.1662*** (-4.6510)	-0.1441*** (-4.0710)	-0.1534*** (-4.3780)
Top1	-1.9978*** (-9.0603)	-1.9107*** (-8.8109)	-1.9141*** (-8.8477)
CRT3	0.4359*** (3.7358)	0.4575*** (3.9546)	0.4363*** (3.7277)
Constant	-6.5298*** (-9.7313)	-6.4157*** (-10.0500)	-7.5402*** (-7.9641)
Year	Yes	Yes	Yes
Industry	Yes	Yes	Yes
N	4,877	4,877	4,877
r ² _a	0.3113	0.3131	0.3110

Note: *, **, *** indicate a notable level of significance at respectively 10%, 5%, and 1%, and the values in parentheses are robust standard errors.

Liu et al. (2022) to classify the sample firms into heavily polluting and non-heavily polluting firms based on the “List of Listed Companies” Environmental Verification Industry Classification and Management developed by the Chinese Ministry of Environmental Protection in 2008. Compared with non-heavily polluting enterprises, heavily polluting enterprises are subject to more stringent environmental regulations and correspondingly higher environmental treatment costs. Due to the pressure of external regulations, heavily polluting enterprises pay more attention to ESG investment, actively take social responsibility, reduce environmental pollution, and promote the symbiosis of economic and environmental benefits. Additionally, heavily polluting enterprises policy environment, financing facilitation, market reputation, and corporate image are all relatively different from those of non-heavily polluting enterprises. To reverse their inherent image in the market and obtain good capital market evaluation and market performance, they need to pay more attention to improving ESG performance. Therefore, compared with non-heavily polluting companies, heavily polluting companies have a stronger desire to increase ESG investment and seek to improve their reputation in the market by changing the perception of their heavy polluting nature, which is reflected in the increase of stock liquidity in the capital market. In this paper, we argue that the effect of the ESG performance of heavy polluters on stock liquidity is stronger than non-heavy polluters. To verify whether the impact of corporate ESG performance on stock liquidity differs by pollution type, we added pollution type (LIFHP) and the interaction term between pollution type and ESG performance (L.ESG×L.IFHP) to Eq. 1. The results in Column (2) of Table 7 show that the regression coefficient of the interaction term between corporate ESG performance and pollution type is 0.0286 and is significantly positively correlated at the 1% level, indicating that the positive contribution of corporate ESG performance to stock liquidity is more significant among heavily polluting firms.

5.3 The impact of corporate ESG performance on stock liquidity: Based on the degree of marketization

Owing to the differences in marketisation processes in different regions of China, the role of the market in resource allocation also varies across regions. Generally, regions with a high degree of marketisation have a better legal environment, smoother information transmission, higher economic levels, and a lower degree of information asymmetry between investors and enterprises. However, in regions with a low degree of marketisation, the legal environment is poor and information asymmetry between investors and enterprises is higher. Therefore, the role of ESG in mitigating information asymmetry is more significant, and the value creation effect is correspondingly stronger in regions with low marketisation, whereas foreign investors are more likely to be influenced by companies' ESG performance when making investment decisions. Summarizing the above, this paper argues that the effect of corporate ESG performance on stock liquidity is stronger in regions with low marketization. To test whether the impact of corporate ESG

performance on stock liquidity differs according to the degree of marketisation, this study adds the degree of marketisation (L.MDI) and the interaction term between marketisation and ESG performance (L.ESG×L.MDI) to Eq. 1. We used the marketisation index of Wang et al. (2019) to measure the marketisation process. The results in column (3) of Table 7 show that the coefficient of the cross-product term is −0.0042 and significant at the 10% level, indicating that the contribution of corporate ESG performance to stock liquidity is more significant in regions with low marketability.

6 Mechanism test

Our analysis leads to an important conclusion that corporate ESG performance can significantly increase a firm's stock liquidity. This section focuses on identifying the channel mechanism of the causal relationship between corporate ESG performance and stock liquidity, in conjunction with previous theoretical analyses. We selected three channel mechanisms: “agency cost,” “foreign ownership,” and “corporate reputation.” To portray the mechanistic paths through which corporate ESG performance affects stock liquidity, we constructed regression models (5) to (7) by drawing on the mediation effects testing process of Wen and Ye (2014). This test procedure is based on the stepwise regression method proposed by Baron and Kenny (1986) and combines the Sobel test and bootstrap method (drawing a self-help sample 1,000 times) to improve the reliability of the regression results.

$$Liquidity_{it} = \alpha_0 + \alpha_1 ESG_{it-1} + \sum \alpha_2 Controls + \sum Year + \sum Ind + \varepsilon_{it} \quad (5)$$

$$Mediator_{it} = \beta_0 + \beta_1 ESG_{it-1} + \sum \beta_2 Controls + \sum Year + \sum Ind + \varepsilon_{it} \quad (6)$$

$$Liquidity_{it} = \gamma_0 + \gamma_1 ESG_{it-1} + \gamma_2 Mediator_{it} + \sum \gamma Controls + \sum Year + \sum Ind + \varepsilon_{it} \quad (7)$$

We selected three sets of mediator variables (Mediator): the first set of variables is agency costs (Cost, the ratio of overhead to operating income) (Ang et al., 2000), which portrays the impact of corporate ESG performance at the corporate operational and governance levels; the second set of variables is foreign ownership (FOREIGN, the natural logarithm of the number of shares held by foreign shareholders among the top ten shareholders) (Chen et al., 2013), which portrays the impact of corporate ESG performance on investor behaviour; the third group of variables is corporate reputation (REP, the corporate reputation score is calculated by factor analysis, and then divided into ten groups according to the lowest to highest corporate reputation score, each group is assigned a value from 1 to 10) (Guan and Zhang, 2019), which portrays the impact of ESG performance on corporate image and market evaluation.

These three types of mediating variables were chosen for the following reasons. First, ESG practices can enhance corporate governance, alleviate the principal-agent problem, reduce the degree of information asymmetry, and enhance investor's

TABLE 8 Mechanism test.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	Cost	Liquidity	FOREIGN	Liquidity	REP	Liquidity
L.ESG	−0.0004*** (−3.6603)	0.0177*** (4.0046)	0.2146*** (12.4601)	0.0086** (1.9961)	0.0051** (2.1467)	0.0174*** (3.8235)
Cost		−2.0112*** (−2.8695)				
FOREIGN				0.0454*** (11.2993)		
REP						0.5124*** (11.6176)
Lev	−0.0914*** (−13.8885)	−0.2082 (−0.8317)	−2.9394*** (−3.4796)	0.1091 (0.4377)	0.7865*** (5.9779)	−0.4740* (−1.7163)
ROA	−0.2693*** (−15.5046)	7.2951*** (9.9170)	25.2167*** (11.5774)	6.6912*** (8.8423)	10.3509*** (26.3391)	2.5236*** (2.8137)
Size	−0.0039*** (−5.1647)	0.8205*** (22.4888)	2.3364*** (20.7669)	0.7221*** (19.5440)	0.5674*** (33.7424)	0.5041*** (11.1860)
Age	0.0011 (0.3737)	−0.2006 (−1.5112)	0.0148 (0.0322)	−0.2036 (−1.5412)	0.2496*** (4.3266)	−0.1705 (−1.2068)
Indep	0.0312** (2.4051)	0.5178 (1.0159)	1.0044 (0.4855)	0.4094 (0.8142)	−0.4969* (−1.7154)	0.8381 (1.6124)
Dual	0.0051*** (2.7565)	0.0128 (0.1634)	0.8660*** (3.1042)	−0.0368 (−0.4700)	−0.0775** (−1.9959)	0.0328 (0.3941)
BM	−0.0022*** (−3.5915)	−0.1584*** (−4.4762)	−0.0012 (−0.0104)	−0.1539*** (−4.4515)	−0.0734*** (−4.7014)	−0.1015*** (−2.7215)
Top1	−0.0108** (−2.2231)	−1.9326*** (−8.9215)	0.1476 (0.1846)	−1.9177*** (−9.0629)	0.7100*** (6.9069)	−1.9807*** (−8.6923)
CRT3	0.0055*** (2.7311)	0.4464*** (3.8324)	0.7437** (2.2946)	0.4016*** (3.4657)	−0.1537*** (−3.5598)	0.4562*** (3.6939)
Constant	0.2024*** (13.4660)	−6.3460*** (−9.4675)	−19.1164*** (−9.0171)	−5.8846*** (−9.0079)	−4.9082*** (−16.4436)	−4.9000*** (−6.4650)
Year	Yes	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes	Yes	Yes
N	4,877	4,877	4,877	4,877	3,785	3,785
Sobel test	2.196**		8.219***		2.089**	
Bootstrap	[0.0004,0.017]		[0.0073,0.0121]		[0.0002,0.0049]	
r2_a	0.3391	0.3123	0.2768	0.3302	0.9232	0.3397

Note: *, **, *** indicate a notable level of significance at respectively 10%, 5%, and 1%, and the values in parentheses are robust standard errors.

investment confidence, thus increasing expectations in the market and contributing to the improvement of stock liquidity. Second, ESG performance is one of the important factors for investors to make investment decisions. The higher the ESG performance, the easier it is to attract the attention of foreign investors, increase the proportion of foreign ownership, optimise the capital structure of enterprises,

reduce risks, supervise the management to actively perform their duties, and create a herding effect in the capital market to improve stock liquidity. Third, the better the ESG performance, the higher the level of social responsibility of enterprises, which is conducive to the establishment of a good brand image and access to more external resources. It also helps companies expand their competitive advantage in the product market, influences investor's decisions in the capital market, and promotes investor's active trading, thereby enhancing stock liquidity. To assess whether the above three paths hold, we test them in a subsequent empirical analysis.

An important feature of ESG performance is that it significantly enhances information transparency and mitigates information asymmetry, thereby reducing agency costs. In Table 8, the regression coefficient of ESG performance on the agency cost variable (Cost) in Column (1) is -0.0004 , significant at the 1% level, indicating that ESG performance, as a type of information disclosure, can effectively alleviate the principal-agent problem between owners and management, avoid opportunistic management behaviour, reduce agency costs, and provide conditions to promote investment. The regression coefficient between cost and stock liquidity in column (2) is -2.0112 , significant at the 1% level, indicating that the reduction of agency costs contributes to the improvement of stock liquidity. This implies that corporate ESG practices can alleviate information asymmetry and reduce agency costs to some extent by disclosing corporate non-financial information and ultimately enhancing the level of stock liquidity. From another perspective, companies with better ESG performance can signal to the market that they have higher corporate governance ratings. By investing more in ESG practices, companies improve their ESG performance and promote governance, which helps reduce agency costs and enhance stock activity.

Columns (3) and (4) of Table 8 show the mechanism identification test for foreign shareholding. In Column (3), the regression coefficient between ESG performance and foreign shareholdings is 0.2146 and significant at the 1% level, implying that foreign investors prefer to invest in companies with good ESG performance. That is, the better the ESG performance, the higher the percentage of foreign shareholdings in the company. The further opening of China's capital market will lead to an increasing number of foreign investors. Foreign investors, primarily institutional investors, increasingly regard ESG as a key driver of long-term growth. Consequently, foreign investors prioritise companies with good ESG performance in their investment decisions. Therefore, ESG performance can contribute to a large extent to the increase of foreign shareholding. Column (4) shows that the regression coefficient between foreign equity ownership and stock liquidity is significantly positive at the 1% level, indicating that foreign investors not only optimise the shareholding structure, improve governance, and enhance corporate value but also enhance the attractiveness of enterprises to other investors, forming a herding effect, generating co-investment behaviour, and promoting stock liquidity.

Finally, we test the mechanism by which ESG performance improves stock liquidity by affecting corporate reputation. Column (5) shows that corporate ESG performance and reputation are significantly positive at the 5% level, indicating that corporate ESG performance helps promote corporate reputation. In column (6), the coefficient of corporate reputation is 0.5124 and significant at the 1% level, which indicates that the higher the corporate reputation, the

better the capital market performance. A good reputation is a unique resource possessed by an enterprise that makes it easier to attract talent, increase investors' investment confidence, build higher customer loyalty, lower the threshold for enterprises to obtain various development resources from different stakeholders, and facilitate maintaining long-term excess profits and improving market positions, thus gaining competitive advantages. A company with a good reputation is bound to gain more recognition in the market, concentrated on the market's pursuit of the company's stock.

7 Conclusion

The ESG concept is highly compatible with China's green development goals, and it has received widespread attention from all walks of life, with more and more domestic companies increasing their investment in ESG. Since scholars have focused on the role of corporate ESG performance in corporate innovation, investment efficiency, and financial performance, it is worthwhile exploring whether ESG performance can enhance corporate performance in the capital market and improve stock liquidity, thus realising the value creation of ESG practices. This study selects data from Chinese A-share listed companies from 2015 to 2020 as a sample to empirically test the impact of corporate ESG performance on stock liquidity and its mechanism of action. The research finds that: 1) Corporate ESG performance has a significant positive impact on stock liquidity; the better the corporate ESG performance, the better its active performance in the capital market and the higher the level of stock liquidity. The results of a series of robustness tests confirmed the findings of this study. 2) The positive effect of corporate ESG performance on stock liquidity is more significant among state-owned enterprises, heavily polluting enterprises, and enterprises in low-market regions. 3) The mechanism tests suggest that good ESG performance reduces agency costs, increases foreign ownership, and improves corporate reputation, thus activating stock trading and improving stock liquidity.

The above research findings help to gain a deeper understanding of the intrinsic mechanism of corporate ESG practices to improve capital market performance, and provide important insights for multiple parties, including governments, enterprises and investors, to promote the construction of ESG systems, increase ESG investment and promote sustainable economic development: first, the value creation effect of ESG practices helps mitigate agency costs, increase foreign ownership, and improve corporate reputation, ultimately improving the performance of firms in capital markets. Therefore, it is beneficial for companies to implement ESG concepts. Secondly, the government should improve ESG-supporting institutional measures for listed companies, especially to strengthen support for non-state enterprises, highly polluting enterprises, and enterprises with low marketization to enhance the vitality and optimize the resource allocation function of the capital market. Finally, investors should establish the ESG investment concept and fully consider corporate ESG performance when making investment decisions. While focusing on the financial performance of the company, they should also consider environmental, social, corporate governance, and other non-

financial attributes of the company, which can help reduce investment risks and obtain sustainable returns.

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

Conceptualization, RC and YL; methodology, RC and YL; software, YL and RC; validation, YL and RC; formal analysis, YL and RC; investigation, YJ and JL; resources, RC, YJ, and YL; data curation, YL and JL; writing—original draft preparation, YL and RC; writing—review and editing, RC, YL, and YJ; visualization, YL and RC; supervision, YJ and JL; project administration, RC; funding acquisition, RC. All authors have read and agreed to the published version of the manuscript.

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Corporate sustainability disclosure on social media and its difference from sustainability reports: Evidence from the energy sector

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The purpose of this study is to examine the sustainability information that energy companies provide on social media and the relationship between that data and that which is shared in conventional sustainability reports. Based on stakeholder theory, we use a sample of Chinese A-share listed energy corporations in 2020 and refer to GRI G4 guidelines to conduct content analysis on their 17,451 tweets from the WeChat platform and 53 sustainability reports. The analysis results show the following: 1) both the sustainability disclosures of Chinese energy firms on WeChat platform and sustainability reports focus on investor and employee dimensions. Among them, the average proportion of investor dimension disclosure to total disclosure is 31.92% and 35.19% on social media and sustainability reports, respectively, and the average proportion of employee dimension disclosure is 27.22% and 17.92%, respectively. However, the two channels show a large difference in the environment and government dimensions. The average proportion of environment disclosure in sustainability reports is 13.44%, while on social media it is only 2.01%. Government disclosure in sustainability reports is 8.24% and as high as 20.43% on social media. (2) Chinese energy firms prefer to provide supplementary information on social media. For example, using the investor dimension as an example, the average proportion of non-GRI information on social media is 71.47%, while that of the sustainability report is only 48.56%. This study helps stakeholders to better understand sustainable information on social media.

KEYWORDS

sustainable management, non-financial disclosure, ESG, CSR, new media

1 Introduction

Under the influence of global sustainability agreements, such as the Kyoto Protocol, the energy industry faces increasing pressure on sustainable development (Chodnicka-Jaworska, 2022; Deng, et al., 2022; Shen, et al., 2022; Wanday and Ajour El Zein, 2022). Especially in recent China, with the introduction of national policies including “carbon peaking and carbon neutrality” (Ju, et al., 2022), Chinese energy firms face severe sustainability challenges. In response, they actively engage in and disclose their sustainable activities (Lu, et al., 2022). According to our statistics, in 2020, 72 (approximately 47%) of the 154 Chinese A-share listed energy firms issued sustainability reports. On the other hand, increasingly popular social media is being utilized by an increasing number of firms for

financial information disclosure (Blankespoor, et al., 2014; Prokofieva, 2015; Yang and Liu, 2017) and sustainability disclosure (Manetti and Bellucci, 2016; Khanal, et al., 2021). For instance, Zhou et al. (2014) discovered that, on Facebook and Twitter, respectively, 7.06% and 3.45% of the material was connected to corporate information disclosure. Amin et al. (2021) conduct research on the UK and find that corporate social responsibility (CSR) disclosures by their sample firms in tweets is on the rise, and 2.9% of firms' tweets are related to CSR. According to our statistics, in 2020, among the 72 Chinese A-share listed energy firms that released sustainability reports, 53 (approximately 74%) registered a WeChat official account (WOA) and posted a large number of sustainability-related tweets on WeChat.

The literature has launched intense discussions on the research on the sustainability information activities of energy firms, e.g., Dilling (2016), Janik et al. (2020), Mamun (2022) and so on. However, most of these studies are limited to traditional sustainability reporting activities, such as reporting in CSR reports, and research on emerging sustainability information activities on social media is lacking. What are the topics of sustainability information on which energy firms focus on WeChat? What is the relationship between sustainability disclosure on WeChat and traditional sustainability reports?

In response to the above questions, we use 53 Chinese A-share listed energy firms that released sustainability reports and WOA in 2020 as a sample. Based on the stakeholder perspectives and referring to the GRI G4 framework¹, we conduct a content analysis on the sample's tweets and sustainability reports. We find that Chinese energy firms pay more attention to investors and employees on social media and in sustainability reports and pay less attention to communities, customers, and suppliers. However, these firms pay more attention to the governmental dimension on social media, whereas in sustainability reports, the environmental component is given more attention. In addition, Chinese energy firms tend to provide more supplementary information outside the GRI framework on social media than in sustainability reports.

The following are the significant contributions of this paper. First, our research expands the understanding of the sustainability information activities of energy firms. Studies already conducted have mostly concentrated on energy companies' disclosure of sustainability information in conventional, cyclical sustainability reports, e.g., Dilling (2016), Janik et al. (2020) and Stuss et al. (2021), and lack an understanding of sustainability information activities in emerging social media channels. This paper provides some interesting references based on Chinese energy firms. Second, this paper compares the content that firms disclose on social media and in sustainability reports, providing a reference for the research field on firms' social media information activities. This helps researchers better understand the commonalities and differences in firms' information disclosures through different channels. For the core stakeholders of the firm, whether in the traditional

sustainability reporting channel or the social media channel, the firm provides a large amount of disclosure for them. However, firms on social media tend to provide information for some non-professional information users and more supplementary information. Finally, this study helps stakeholders such as socially responsible investors (SRI) to better understand and use sustainable information in corporate WeChat tweets.

2 Literature review

2.1 Sustainability disclosure in the energy sector

Sustainability disclosure is the non-financial information provided to stakeholders to obtain legitimacy and key resources from them (Herzig and Schaltegger, 2006; Milne and Gray, 2007; Adams and Whelan, 2009). As one of the most significant foundational sectors of the national economy and having a substantial effect on the environment, the energy industry is of great concern to stakeholders, including the community and governments. In response to these concerns, energy firms are increasingly devoted to sustainability disclosure activities (Jenkins and Yakovleva, 2006; Perez and Sanchez, 2009; Lu, et al., 2019; Stuss, et al., 2021). Although some evidence shows that energy firms use voluntary sustainability standards to enhance the quality of their sustainability disclosure (Alazzani and Wan-Hussin, 2013), there are still some problems in energy firms' sustainability information activities.

First, the disclosure lacks comparability. Through a case study of the 10 largest mining firms in the world, Jenkins and Yakovleva (2006) find that there are considerable differences in firms' report content and style. Szczepankiewicz and Mućko (2016) conduct a content evaluation of CSR reports for the Polish energy and mining industry and find that these reports are similar only in structure but are significantly different regarding specific topics. Ng et al. (2022) study the sustainability reports of Ghana's oil industry and mining sectors and find that the comparability of the information between these firms is weak.

Second, the materiality of the disclosure is low. Guenther, et al. (2006) conduct an analysis of the sustainability disclosure of international firms in the mining, oil and gas sectors and find that, on average, each company only reported one-third of the indicators in the GRI framework. Dilling (2016) study the sustainability reports of 20 Canadian listed mining and energy firms, which revealed similar problems. The quality of their reports was low. Mamun (2022) uses a sample of Australian power firms and finds that most of the sample firms failed to disclose more than two-thirds of the GRI indicators and preferred to use declarative information rather than quantitative data.

Third, the problem of selective manipulation in disclosure is widespread. Boiral (2013) analyse 23 high-rated ESG reports in the energy and mining sectors. According to the results, almost 90% of unfavourable material events were not acknowledged, which violates the GRI guidance on the principles of balance, completeness and transparency. Dong et al. (2014) study the Chinese mining industry and show that its sustainability disclosure is more related to the

¹ In 2020, the sample enterprises studied in this paper mostly used GRI G4 as a reference when compiling their sustainable development reports. For example, Jiangsu Guosen Co., LTD. disclosed that "the report was prepared according to the G4 guidelines of the Global Reporting Initiative (GRI)".

needs of the central government and global consumers but ignores the requirements of mining organizations, local communities, and employees. [Nwagbara and Belal \(2019\)](#) find that Nigerian oil firms, despite serious criticism, still commit to engaging in active impression management by using sustainability disclosure. In the study of [Janik et al. \(2020\)](#), during 2020, European Union (EU) energy firms expressed great concerns over greenhouse gas issues but lacked sufficient descriptions in the disclosure of specific actions.

Since there are significant discrepancies in the amount and quality of sustainability disclosure made by energy companies, some studies have focused on the driving factors of their disclosure, including government supervision ([Dong and Xu, 2016](#)), CEO declarations ([De-Miguel-Molina, et al., 2019](#)) and regional economic development ([Karaman, et al., 2021](#)). However, worth noting is that these studies on the sustainability disclosure of energy firms have mostly concentrated on traditional periodic reports, namely, sustainability reports, and have lacked an explanation of sustainability disclosure in other new media channels (such as WeChat).

2.2 Social media and corporate sustainability disclosure

Corporate information efforts have been significantly impacted by the emergence of social media, which now includes some updated features, including removing media intermediaries, breaking the elite's control, and higher timeliness and dynamics ([Lee, et al., 2013](#); [Lyon and Montgomery, 2013](#); [Zheng, et al., 2018](#)). These characteristics make social media helpful for firms to carry out self-interested information dissemination ([Blankespoor, et al., 2014](#); [Lee, et al., 2015](#); [Jung, et al., 2017](#); [Yang and Liu, 2017](#)), thus guiding stakeholders' impressions ([Lee, et al., 2015](#); [Manetti and Bellucci, 2016](#); [Saxton, et al., 2019](#); [She and Michelon, 2019](#); [Russo, et al., 2022](#)). However, they also create increases in firms' external supervision, expand the uncertainty of public opinion ([Hales, et al., 2018](#); [Ang, et al., 2020](#); [Lepore, et al., 2022](#); [Turzo, et al., 2022](#)), and even force firms to be more responsive ([Lei, et al., 2018](#); [Fan, et al., 2020](#); [Dube and Zhu, 2021](#); [Zhang and Yang, 2021](#); [Shao and He, 2022](#)). [Tench and Jones \(2015\)](#) argue that social media provide stakeholders with a more radical and open discussion environment, which challenges firms' attempts to maintain their social legitimacy through traditional rules. [Stohl et al. \(2017\)](#) even find that some firms are inclined to inhibit employees from discussing and participating in corporate social responsibility on social media.

Research on firm sustainability disclosure on social media has mainly focused on the following topics. First, some studies have investigated the content and theme of sustainability disclosure on social media. [Toppinen et al. \(2015\)](#) find that the most common topics of global pulp and paper manufacturing firms on Twitter are the environment and then community. [Amin et al. \(2021\)](#) study the tweets from UK firms in the FTSE 350 index and suggests that 2.9% of the tweets are CSR-related. [Ramananda and Atahau \(2020\)](#) find that compared to annual reports, Indonesian companies post less information related to Corporate Social Responsibility on social media. [ElAlfy et al. \(2020\)](#) take a sample of S&P 500 firms

and find that tweets related to sustainability are mostly related to their core businesses. [Gómez-Carrasco et al. \(2021\)](#) study the tweets of Spanish banks on Twitter and argue that supplementary CSR information on social media is more concerned by internal stakeholders, while core CSR information is more concerned by external stakeholders. Second, some studies have been concerned over the motivations for corporate sustainability disclosure on social media. [Amin et al. \(2021\)](#) figure that corporations with more independent directors and female directors provide more sustainability disclosure on Twitter. [Baboukardos et al. \(2021\)](#) figure that corporations with better CSR performance make more additional relevant disclosures on social media. Third, some studies have revealed the consequences of sustainability disclosure on social media. [Yang et al. \(2020\)](#) figure that CSR activities on social media benefit firms from obtaining higher brand equity. [Pu et al., \(2022\)](#) figure that firms use social media to restore the reputational damage caused by negative sustainability events. According to [Lepore et al. \(2022\)](#), social media can enhance the ability of independent directors to advance corporate social responsibility.

However, there are currently few relevant discussions on the social media disclosure of energy firms, except for [Pizzi et al. \(2021\)](#), who discuss the CSR strategy of oil and gas firms on social media communication with stakeholders. The literature has provided few references for the stakeholder information that is preferred by energy firms on social media and the connection of sustainability information activities between firms' social media and conventional sustainability reports.

3 Research design

3.1 Data sources

Certain social media services, including Facebook and Twitter, are restricted in China due to legislative measures and other aspects of the Chinese government's policies. Thus, we select WeChat as the object social media for the following reasons. First, WeChat does not have a content limit, so it allows a larger information load. Second, WeChat has the largest user base in mainland China. For example, in 2020, WeChat had 1.09 billion daily active users and 360 million daily users who visited WOAs².

According to the definition of the energy industry in the China Energy Statistical Yearbook ([Liu, 2020](#)), the Chinese energy industry includes the 1) coal mining and washing industry, 2) oil and natural gas extraction industry, 3) petroleum processing, coking and nuclear fuel processing industry, 4) electricity, heat production and supply industry, and 5) gas production and supply industry³. In 2020, there were 154 listed firms in China's energy industry, of which 53 firms released sustainability reports and established WOA

2 Data source: https://www.thepaper.cn/newsDetail_forward_10949031.

3 The corresponding CSRC industry codes (2012 version) are B06, B07, C25, D44 and D45, respectively.

TABLE 1 Variable definition.

Variable	Definition
Variables of sustainability disclosure on social media	
Wechat_all	The total level of sustainable information disclosure of social media channels, is the sum of the disclosure level of the seven stakeholder dimensions
Wechat_en	The level of sustainable information disclosure in the environmental dimension of social media channels is the sum of disclosure levels in all aspects of the environmental dimension
Wechat_cu	The level of sustainable information disclosure in the customer dimension of social media channels is the sum of disclosure levels in all aspects of the customer dimension
Wechat_em	The level of sustainable information disclosure in employee dimension of social media channels is the sum of disclosure levels in all aspects of employee dimension
Wechat_su	The level of sustainable information disclosure in the supplier dimension of social media channels is the sum of disclosure levels in all aspects of the supplier dimension
Wechat_co	The level of sustainable information disclosure of community dimension of social media channels is the sum of disclosure levels of all aspects of community dimension
Wechat_go	The level of sustainable information disclosure in government dimension of social media channels is the sum of disclosure levels in all aspects of government dimension
Wechat_in	The level of sustainable information disclosure in the investor dimension of social media channels is the sum of disclosure levels in all aspects of the investor dimension
Variables of sustainability disclosure in sustainability report	
Report_all	The total level of sustainable information disclosure in sustainable reporting channels is the sum of the disclosure levels of the seven stakeholder dimensions
Report_en	The level of sustainable information disclosure in the environmental dimension of sustainable reporting channel is the sum of the disclosure levels of all aspects of the environmental dimension
Report_cu	The level of sustainable information disclosure in the customer dimension of sustainable reporting channel is the sum of disclosure levels in all aspects of the customer dimension
Report_em	The level of sustainable information disclosure in the employee dimension of sustainable reporting channel is the sum of disclosure levels in all aspects of the employee dimension
Report_su	The level of sustainable information disclosure in the supplier dimension of sustainable reporting channel is the sum of disclosure levels in all aspects of the supplier dimension
Report_co	The level of sustainable information disclosure in the community dimension of sustainable reporting channel is the sum of the level of disclosure in all aspects of community dimension
Report_go	The level of sustainable information disclosure in the government dimension of sustainable reporting channel is the sum of the level of disclosure in all aspects of government dimension
Report_in	The level of sustainable information disclosure in the investor dimension of sustainable reporting channel is the sum of the level of disclosure in all aspects of investor dimension

for at least 1 year. [Supplementary Appendix SA](#) lists the names of the listed firms in the Chinese energy industry involved in this research. Subsequently, we use Python to obtain all of the tweets published by these 53 energy listed firms on their WOA in 2020—a total of 17,451; their 53 sustainability reports came from CNINF (<http://www.cninfo.com.cn/>).

3.2 Content analysis

We refer to the GRI G4 sustainability guidelines to establish a content analysis system and use Atlas. ti 8.0 to classify the WeChat tweets and sustainability reports. According to stakeholder theory ([Freeman, 1984](#)), our content analysis system includes 7 first-level dimensions: environment,

customer, employee, supplier, community, government and investor. 9 to 22 second-level subdimensions make up each first-level dimension; for example, the environment dimension includes 16 second-level subdimensions: Strategy and Analysis (EN01), Organizational Profile (EN02), Materials (EN03), Energy (EN04), Water (EN05), Biodiversity (EN06), Emissions (EN07), Effluents and Waste (EN08), Products and Services (EN09), Compliance (Environment) (EN10), Transport (EN11), Overall (EN12), Environmental Grievance Mechanisms (EN13), Product and Service Labelling (EN14), Stakeholder Engagement (EN15) and Non-GRI Others (EN16). A content taxonomy and information examples are reported in [Supplementary Appendix SB](#).

We developed the codebook based on the index content of GRI G4. Firstly, the first researcher classified and coded the G4 index

TABLE 2 Overall and first-level dimension analysis of sustainability disclosure on social media.

	Measure	Observation	Mean	Ratio (%)	Standard deviation	Minimum	Medium	Maximum
(1)	Wechat_all	53	748.8	100	981.1	3	449	6039
(2)	Wechat_en	53	15.08	2.01	21.96	0	6	101
(3)	Wechat_cu	53	80.58	10.76	108.3	0	42	513
(4)	Wechat_em	53	203.8	27.22	353.7	0	92	2331
(5)	Wechat_su	53	1.43	0.19	2.7	0	0	13
(6)	Wechat_co	53	55.83	7.46	69.7	0	33	340
(7)	Wechat_go	53	153	20.43	213	1	110	1368
(8)	Wechat_in	53	239	31.92	311.7	1	115	1726

content according to stakeholders. At the same time, by reading the corporation's social media tweets, the categories disclosed by the enterprise but not included in the GRI framework were added to the codebook. Subsequently, a second researcher worked independently to classify the G4 indicators into each stakeholder dimension and sort out the non-GRI framework's contents. Finally, the differences between the two groups of people in coding classification were discussed, and the codebook is included in [Supplementary Appendix SB](#).

While coding and scoring the content of tweets, our two groups of researchers independently coded and scored the tweets according to the code book. Finally, the coding and scoring of the two groups were compared and discussed to determine the final score of each sample.

In the scoring process, first, we score according to the second-level subdimension of the system. When tweets or sustainable development reports provide qualitative information about this sub-dimension, the score is 1, and the score is 2 when numerical data is provided. Then, we aggregate the scores of all of the second-level subdimensions under the first-level dimension to form first-level variables used in our main analysis. After completing the aforementioned stages, we defined 16 first-level dimension variables (see [Table 1](#)), among which 8 are social media variables and 8 are sustainability report variables.

4 Main analysis results

4.1 Analysis results of the first-level dimension disclosure

In this section, we first compare the disclosure of the two channels based on the 7 first-level dimensions of stakeholders.

4.1.1 Content analysis of the first-level dimension of sustainability disclosure on social media

[Table 2](#) lists 53 companies in the energy sector and their descriptive statistics for overall social media channels and the first-level dimension of sustainable information disclosure. Among them, the mean and median of the overall disclosure level wechat_all are 748.8 and 449 respectively. Rows (2) to (8) report the disclosure of the environment, customer, employee,

supplier, community, government and investor variables wechat_en, wechat_cu, wechat_em, wechat_su, wechat_co, wechat_go and wechat_in respectively horizontal stats. Investors, employees, and government are the three aspects with the highest level of transparency, with mean (median) values of 239 (115), 203.8 (92), and 153 (110); The dimensions are customer dimension, community dimension, environment dimension and supplier dimension, and their mean (median) values are 80.58 (42), 55.83 (33), 15.08 (6), 1.43 (0) respectively. In addition, column (4) in [Table 2](#) lists the proportion of the disclosure level of each dimension to the overall disclosure level. The three having the greatest percentage of disclosure level among them are the government, employee, and investor aspects, and their disclosure proportions are 31.92%, 27.22% and 20.43%⁴ respectively, accounting for 80% of the overall disclosure level. The above results show that the stakeholders most concerned by Chinese energy firms in their sustainability disclosure activities on social media are investors, employees and the government.

4.1.2 Content analysis of the first-level dimension of sustainability disclosure in sustainability reports

[Table 3](#) lists the descriptive statistics of the overall sustainability reports of 53 energy industry firms and the first dimension's sustainability information disclosure. The mean and median of the overall disclosure level report_all are 83.91 and 34.92, respectively. Rows (2) to (8) report the disclosure of environment dimension, customer dimension, employee dimension, supplier dimension, community dimension, government dimension and investor dimension variables report_en, report_cu, report_em, report_su, report_co, report_go and report_in, respectively horizontal stats. Investor, employee, and environment are the three having the greatest amount of transparency, with mean (median) values of 29.53 (28), 15.04 (13) and 11.28 (10); The dimensions are customer

4 The information ratio for level 1 subdimensions is calculated by dividing the average of the subdimension indicators by the average of the overall scoring indicator Wechat_all. For instance, the total score indicator Wechat_all's 748.8 divided by the average of the environment dimension variable Wechat_en's 15.08 yields a percentage of 15.08%.

TABLE 3 Overall and first-level dimension analysis of sustainability disclosure in sustainability reports.

	Measure	Observation	Mean	Ratio (%)	Standard deviation	Minimum	Medium	Maximum
(1)	Report_all	53	83.91	100.00	34.92	27	79	168
(2)	Report_en	53	11.28	13.44	9.97	1	10	44
(3)	Report_cu	53	9.38	11.18	6.51	0	10	23
(4)	Report_em	53	15.04	17.92	7.81	2	13	36
(5)	Report_su	53	2.6	3.10	2.5	0	2	9
(6)	Report_co	53	9.17	10.93	5.24	0	8	25
(7)	Report_go	53	6.91	8.24	3.95	0	6	17
(8)	Report_in	53	29.53	35.19	11.22	7	28	59

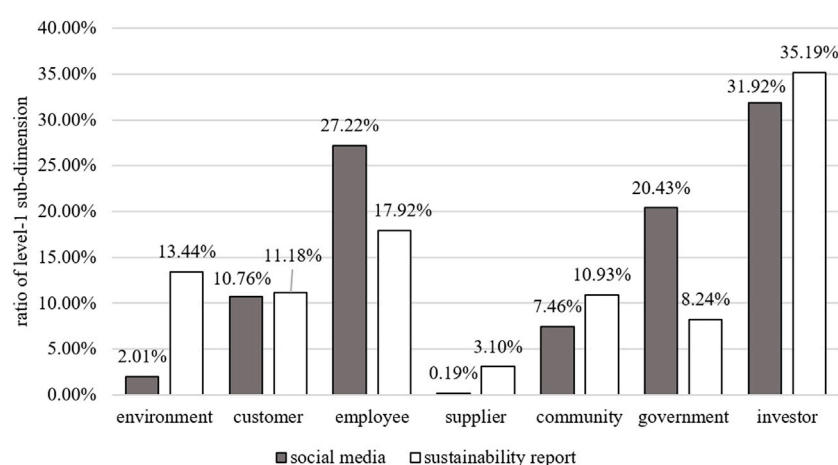


FIGURE 1

Comparative analysis of sustainability disclosure in different channels.

dimension, community dimension, government dimension and supplier dimension, and their mean (median) values are 9.38 (10), 9.17 (8), 6.91 (6), and 2.6 (2) respectively. In addition, column (4) in Table 2 lists the proportion of the disclosure level of each dimension to the overall disclosure level. The three with the most transparency are the investor, the employee, and the environment, and their disclosure proportions are 35.19%, 17.92% and 13.44%, respectively, accounting for 66% of the overall disclosure level.

4.1.3 Comparative analysis of the first-level dimension of the two channels

Figure 1 reports the comparative results of the disclosures of Chinese energy corporations in WeChat and sustainability reporting channels according to the stakeholder dimension.

First of all, there are differences in the dimensions of stakeholders concerned by energy industry companies through different channels. The first three parameters of sustainability reports are investors (35.19%), employees (17.92%), and the environment (13.44%), while the first three parameters of WeChat are investors (31.92%), employees (27.22%), and the

government (20.43%). The third dimension on social media is the governmental dimension (20.43%), but it ranks only sixth in sustainability reports (8.24%) with a difference of more than two times. Moreover, in the sustainable development report, the third dimension is the environmental dimension (13.44%), but it only ranks sixth (2.01%) on social media, a difference of more than six-fold. These results suggest that Chinese energy firms prefer to provide more environmental information than governmental information in sustainability reports but prefer to provide governmental information on social media, while the government receives less attention in sustainability reports.

Second, energy firms focus on the same stakeholder dimension through different channels. For example, the supplier dimension has the lowest disclosure ratio of the two channels. This might be due to the fact that energy companies are upstream in the supply chain or provide their own raw materials, meaning suppliers have less sway over them and are less concerned about sustainability disclosure. Additionally, in the two channels, the investor and employee dimensions account for a large proportion, indicating that these two stakeholder dimensions are the focus of firms.

TABLE 4 Comparative analysis of the second-level subdimensions of investors in different channels.

Level-2 indicator	Definition	Observation	Average reporting ratio (social media) (%)	Average reporting ratio (sustainability report) (%)
IN02	Organizational profile (investor)	53	12.49	23.40
IN04	Stakeholder engagement (investor)	53	0.89	11.31
IN06	Governance (investor)	53	1.11	6.98
IN08	Economic performance (investor)	53	2.62	5.49
IN18	Non-GRI others (investor)	53	81.80	39.93

TABLE 5 Comparative analysis of the second-level subdimensions of employees in different channels.

Level-2 indicator	Definition	Observation	Average reporting ratio (social media) (%)	Average reporting ratio (sustainability report) (%)
EM02	Ethics and integrity (employee)	53	9.87	2.39
EM03	Stakeholder engagement (employee)	53	1.64	11.44
EM04	Economic performance (employee)	53	0.75	4.39
EM08	Occupational health and safety (employee)	53	0.24	4.52
EM09	Training and education (employee)	53	10.01	15.43
EM22	Non-GRI others (employee)	53	76.50	55.72

4.2 Analysis results of the second-level subdimension of the two channels

The previous analysis suggests that the stakeholder dimensions that Chinese energy firms pay the most attention to in the two channels are investors and employees, and the accumulated proportion of the disclosure of both exceeds 50%. However, is there a reporting difference between these two stakeholder dimensions in the second-level subdimension? We discuss this issue in this section.

4.2.1 Comparative analysis of the second-level subdimensions of investors in different channels

Table 4 shows the comparative analysis of the proportion of the second subdimensions of the two channels for the investor dimension. We report the average proportion of investors' second-level subdimension scores to the first-level dimension scores under the two channels. For brevity, we report only the second-level subdimensions that are heavily disclosed within the two channels. Among them, except for the indicator Non-GRI Others (Investor) (IN18), other indicators are under the GRI framework. On social media, Chinese energy firms are keen to disclose information outside the GRI framework, with the proportion of IN18 is as high as 81.80%. Additionally, they are more concerned about the disclosure of Organization Introduction (IN02), accounting for an average of 12.49%,

while other second-level subdimensions generally do not exceed 3%. In sustainability reporting channels, except for the indicator IN18, the second-level subdimension Organization Introduction (IN02) receives more disclosure, accounting for an average of 23.40%. Moreover, Stakeholder Engagement (Investor) (IN04), Governance (Investor) (IN06) and Economic Performance (Investor) (IN08) also receive a certain level of disclosure, with an average disclosing proportion of 11.31%, 6.98% and 5.49%.

4.2.2 Comparative analysis of the second-level subdimensions of employees in different channels

Table 5 shows the results of the comparative analysis of the proportion of sustainability disclosure of the second-level subdimension under the employee dimension of the two channels. Similar to Table 4, we report only the second-level subdimensions that are heavily disclosed. The indicators except for Non-GRI Others (Employee) (EM22) are under the GRI framework. Chinese energy firms disclose Non-GRI Others (EM22) as high as 76.50% on social media; after EM22, the following subdimensions are Training and Education (Employee) (EM09) and Ethics and Integrity (Employee) (EM02), which account for an average of 10.01% and 9.87%, respectively. The other second-level subdimensions on social media generally do not exceed 2%. In the sustainability reporting channel, the second-level subdimension Non-GRI Others (Employee) (EM22)

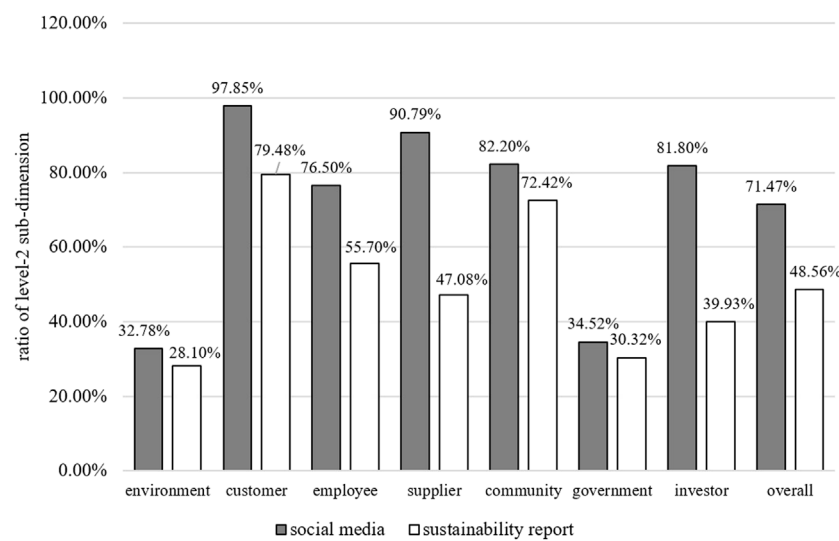


FIGURE 2

Comparative analysis of non-GRI disclosure in different channel.

obtains the highest reporting proportion (55.72%), but it is lower than the proportion on social media. Then, Training and Education (Employee) (EM09) and Stakeholder Engagement (Employee) (EM03) receive more disclosure, and their average proportions are 15.43% and 11.44%, respectively. Unlike disclosure on social media, the subdimension of Ethics and Integrity (Employee) (EM02) is reported relatively lower in sustainability reports, with an average proportion of only 2.39%.

4.2.3 Comparative analysis of non-GRI disclosure in different channels

The previous analyses in Sections 4.2.1, 4.2.2 reveal that under the investor and employee dimensions, Chinese energy firms show different non-GRI disclosure proportions in different channels. In this section, we further discuss the case under the dimension of all stakeholders.

Figure 2 shows the proportions of non-GRI disclosures under all stakeholder dimensions in both channels. Among them, for social media, the non-GRI disclosure proportions of Chinese energy firms in terms of customers, suppliers, communities, investors and employees are 97.85%, 90.79%, 82.20%, 81.80% and 76.50%, respectively, while the non-GRI disclosures in the government and environment dimensions are less, accounting for 34.52% and 32.78%, respectively. For sustainability reports, the non-GRI disclosure proportions in terms of customers, communities and employees are 79.48%, 72.42% and 55.70%, respectively; in the dimensions of suppliers, investors, government and the environment, non-GRI disclosure is less, with proportions of 47.08%, 39.93%, 30.32% and 28.10%. The dimensions with the smallest difference between the two channels are environment and government, and the difference is approximately 4%. Suppliers, investors and employees have larger differences, and the largest is for the supplier dimension at approximately 43%. To more intuitively observe the proportion of non-GRI disclosure at the total level, in the last column of the graph, we sum up the non-GRI disclosure scores of all

second-level subdimensions, divide by the total score, and then take the average value and mark it as “Overall.” We find that the overall proportion of non-GRI disclosures on social media channels is 71.47%, while that in sustainability reports is 48.56%, indicating that the proportion gap between the two channels exceeds 20%. Therefore, compared with sustainability reports, Chinese energy firms tend to provide more supplementary information outside the GRI framework on social media. We argue that the reason for this difference may be that, on social media, firms consider more the needs of non-professional information users, e.g., employees and community residents, which leads them to make more diversified disclosures that are beyond the framework of GRI.

5 Discussion and conclusion

This study makes a content analysis on the sustainability disclosure of Chinese energy corporations in WeChat and sustainability reporting channels. Based on stakeholder theory and referring to the GRI G4 framework, we analyse the WeChat tweets and sustainability reports published by Chinese energy firms in 2020 and find that first, both the sustainability disclosures of Chinese energy corporations on WeChat and sustainability reports focus on investor and employee dimensions but show a large difference in the environmental and government dimensions. Second, firms tend to provide more supplementary information outside the GRI framework on social media.

The practical significance of this paper is to help stakeholders interested in sustainable disclosure in corporate social media tweets, such as SRI, better understand the characteristics and implications of social media disclosure activities so that they can more effectively utilize this new incremental information.

This article also has some deficiencies. First, the WeChat platform allows firms to filter negative comments, so the

displayed comments are incomplete, and we cannot analyse the communication between firms and stakeholders. Second, some sample firms do not have independent WOAs, and their social media disclosures are realized through the accounts of their parent firms. Since it is difficult to distinguish the content, we cannot include these firms in our analysis. Third, due to the limitations of length and workload, we did not specifically analyze the reasons for the difference in information disclosure between sustainable development reports and social media. At the same time, due to the limitations of space, this paper only analyzes the information disclosure in 2020 and does not compare the specific quantity and nature of the content. We will supplement these questions in subsequent research. In the future, we expect investigating these problems through questionnaire analysis, field research and case 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

MZ and MW contributed to the conception and design of the study, performed the statistical analysis, and wrote the first draft of the manuscript. All authors contributed to the article and approved the submitted version.

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Supplementary material

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“Black box operation” in carbon reduction: Based on empirical evidence of carbon transfer by subsidiaries of Chinese enterprises

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Avoiding the transfer of “carbon” and encouraging the digestion of “carbon” are essential to promote the green and low-carbon transformation of China’s economy. In accordance with the standpoint of off-site subsidiaries, this paper examines the transfer of “carbon” from high-carbon enterprises using the data of A-share listed companies from 2009 to 2018 using a DID approach and the 2013 China carbon emissions trading pilot as a quasi-natural experiment. As demonstrated by the reach findings: (1) Part of the effect of corporate “carbon reduction” is achieved by shifting high-carbon sectors. (2) As demonstrated in mechanism analysis, when high-carbon companies face the dual cost pressure of R&D expenditure and purchasing carbon trading rights, they will establish subsidiaries to avoid the parent company’s pressure to lessen emissions. As revealed in heterogeneity analysis. (3) companies with stronger R&D capabilities and higher success rates are more willing to respond to the impact of carbon trading policies with technological upgrades. Companies with weaker R&D capabilities and higher failure rates are more likely to choose to transfer “carbon” to avoid the “dual cost” of R&D failures. (4) Owing to the constraint of the migration threshold, the trajectory of “carbon” transfer is primarily domestic interregional transfer supplemented by cross-country transfer. (5) Larger enterprises emitting more “carbon”, are not only more likely to pay more “carbon” reduction costs in the face of carbon policy shocks, are but also more likely to shift “carbon”. This study not only provides a new perspective to explain the “carbon” transfer phenomenon in China, but also provides crucial policy implications for further strengthening environmental governance as well as regional joint prevention and control in China.

KEYWORDS

pollution transfer, carbon emission transfer, carbon emissions trading, green development, offsite subsidiaries

1 Introduction

How to effectively cut down “carbon” emissions has become the focus of environmental policies in the world today, among which the carbon emissions trading system is considered to be a paramount tool for cutting down “carbon” emissions and mitigating climate warming. In 2013, China officially launched the carbon trading market in the pilot regions. As demonstrated by the research findings, implementing the carbon trading policies has not only promoted the R&D and innovation of green technologies in the pilot regions, but also has exerted a profound influence on the “emission reduction” of enterprises (Pan and Wang, 2022; Wu et al., 2022), but is there any “underhanded operation” in this? Is “carbon reduction” on the basis of enterprises’ own internal transformation or on the transfer of “carbon” (In this paper, the transfer of carbon

emissions by enterprises across regions is uniformly referred to as “carbon” transfer)? There is little discussion in the literature.

As China’s environmental protection policy system continues to improve and the types of policies as well as instruments become more diverse, especially after the implementation of carbon trading policies, high-carbon companies will face pressure from both the quantity and intensity of environmental regulations. To avoid being closed down and banned, enterprises must either transform and upgrade or transfer “carbon”. The former is in line with policy expectations, using environmental regulation to “push” high-carbon enterprises to transform and upgrade, but the initial investment in this approach is large and slow. Apart from that, enterprises may face the dual cost of R&D expenditure and the cost of purchasing carbon emission rights arising from the failed transformation. The transfer of “carbon” can effectively avoid the disadvantageous influence of carbon trading policies. In terms of research on carbon transfer in China, Han et al. (2020) found that Jiangsu, Shandong, Inner Mongolia, Hebei and Liaoning have the largest carbon emission outflows, with more than 70.00 Mt to other domestic provinces. While Henan, Shanxi, Guangdong, Inner Mongolia and Yunnan are major importing regions, most of which with more than 60.0 Mt of domestic carbon emission inflows, this partly explains the shift in China’s carbon emissions. In recent years, this pollution transfer, or “pollution refuge”, hypothesis has been extensively discussed by domestic and foreign scholars (Brunnermeier and Levinson, 2004; Erdogan, 2014; Song et al., 2021; Shen et al., 2017). Most scholars have also confirmed the existence of this hypothesis. What’s more, most of these studies fix their attention on the overall transfer of firms, but the drawback is also more apparent, namely, the high cost of relocation. On this basis, scholars began to concentrate on the lower-cost and more concealed method of pollution transfer, i.e., transferring pollution through the intracompany group (Becker and Henderson, 2000; Keller and Levinson, 2002; List et al., 2003; Song et al., 2021; Dechezleprêtre et al., 2022). Aside from that, there are certain restrictions on such transfers: not only does it require the company to have an intragroup company in an off-site location, but it is also limited by the geographical influence of the intragroup company. On this basis, this paper probed deep into the transfer of high-carbon emitting sectors through the establishment of subsidiaries across regions under carbon trading policies. This transfer mode not only tremendously expands the market scale of the enterprise and cuts down transaction costs, but also makes full use of the local resource endowment through the rational distribution of subsidiaries, thus noticeably ameliorating the overall income of the enterprise. Meanwhile, it enables the parent company to avoid the carbon trading policy and alleviates the pressure on the parent company to “lessen emissions and carbon”. Even when the parent company shifts too much carbon emissions to cut down the amount of carbon emissions below the set amount of carbon trading, it can sell carbon trading rights to gain some revenue.

The carbon trading policy is originally intended to help enterprises “curtail carbon emissions” and force them to transform and upgrade, rather than inducing them to transfer “carbon”. This not only defeats the original intention of the state to “lessen carbon emissions” in general but also weakens the guiding role of carbon trading policy. It also cut downs the cost of carbon emissions, weakens the motivation of enterprises to “lessen emissions and decrease carbon”, and curbs the momentum of green technology innovation, transformation and upgrading of enterprises. Under this background, it is essential to probe deep into the intrinsic motivation and characteristics of the

transfer of “carbon” by high-carbon enterprises. On this basis, to “prescribe the right medicine” to avoid the transfer of “carbon” by high-carbon enterprises, so as to ensure the effective implementation of carbon trading policy, which is crucial to promote the green and low-carbon transformation of China’s economy.

This paper is also bound up with the literature on carbon trading systems. Most scholars domestically and internationally have affirmed the role of carbon trading policies in upgrading regional industrial structures (Liu and Chen, 2022). On the enterprise side, carbon trading policy is advantageous for pushing R&D innovation ahead (Liu and Zheng, 2017), elevating the efficiency of corporate investment and ameliorating the short-term value of enterprises (Zhang and Wu, 2022). The most relevant paper examined the impact of carbon trading on OFDI and finds that regions heighten their OFDI on account of carbon trading policies (Guo and Xiao, 2022), which confirms that firms shift their “carbon” to cut down the pressure to lessen emissions after implementing carbon trading policies. Nevertheless, the above literature investigated nothing more than the impact of carbon trading policies at the provincial level. What’s more, it failed to explore the impact of carbon trading policies at the firm level. As a consequence, our paper is intended to examine the impact at the firm level to further fill the gap left in the above literature. Aside from that, the literature mentioned above investigated nothing but the impact of carbon trading policies on the transfer of carbon across borders. But it did not consider that most enterprises are unable to transfer carbon across borders as a result of their own business level and economic capacity. This paper further investigates the impact of carbon emissions trading policy on the transfer of pollution by enterprises not only in domestic cross-regional “carbon” transfer but also in the transnational transfer of enterprises.

Compared with the above literature, the primary contributions of this paper are as follows.

First and foremost, this paper examines “carbon” transfer under a carbon trading policy in accordance with the viewpoint of off-site subsidiaries, which complements and enriches the “pollution refuge” hypothesis. Most of the existing studies on the pollution refuge hypothesis fix their attention on the way of transfer within the enterprise or group, but there are few papers that examine the transfer of pollution in the way of setting up subsidiaries.

Furthermore, this paper expands the issue of “carbon reduction” under a carbon trading policy in accordance with the viewpoint of “carbon” transfer. Most of the existing studies on carbon trading systems concentrate on the impact of carbon trading policies on the upgrading of regional industrial structure and technological innovation of enterprises. Nonetheless, is this on the basis of enterprises’ own internal transformation and upgrading, or is it in line with enterprises’ transformation and upgrading by transferring high “carbon” sectors? There is little explanation in existing studies. In this paper, we explain that the transformation and upgrading of enterprises or regions is partly in line with the transfer of high carbon sectors. This paper expands on the issue of “carbon reduction” under the carbon trading policy.

Finally, this paper provides policy ideas for promoting the green and low-carbon transformation of China’s economy. The original intention of carbon trading policy is to promote enterprises to “reduce carbon emissions” rather than to induce enterprises to transfer “carbon”. This not only goes against the country’s original aspiration of “reducing carbon emission” in total volume but also weakens the guiding role of carbon trading policy. It also reduces the

cost of carbon emissions for enterprises, weakens the incentive for enterprises to “reduce carbon emissions”, and restrains the momentum of enterprises to carry out green technology innovation, transformation and upgrading. Based on an in-depth analysis of the internal motivation and characteristics of the transfer of “carbon” by high-carbon enterprises, this paper provides policy ideas for avoiding the transfer of “carbon” by high-carbon enterprises, ensuring the effective implementation of carbon trading policies, and promoting the green and low-carbon transformation of China’s economy.

2 Institutional background and theoretical

2.1 Institutional background

Carbon trading is an economic instrument that uses market mechanisms to deal with the climate problem. It uses market forces to transform the environment into a factor of production and trade carbon emission rights as a valuable asset in the market. Since the Kyoto Protocol came into effect, carbon trading systems have developed rapidly. Aside from that, countries and regions have started to establish intraregional carbon trading systems to put their carbon emission reduction commitments into reality. Seventeen carbon trading systems were built across four continents in the decade from 2005 to 2015, and in recent years, the percentage of carbon emissions covered by carbon trading was more than two times higher than that covered by EU carbon trading when it was launched in 2005. China’s carbon emissions trading system started with the State Council’s Decision on Accelerating the Cultivation and Development of Strategic Emerging Industries issued in 2010. In October 2011, the National Development and Reform Commission issued the Notice on the Pilot Work of Carbon Emissions Trading, approving the pilot work of carbon emissions trading in seven provinces and cities, namely, Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong and Shenzhen. Since 2013, the seven pilot carbon markets have started online trading one after another, covering nearly 3,000 key emission units in more than 20 industries, such as electricity, steel and cement. As of 30 September 2021, the cumulative volume of allowances traded in the seven pilot carbon markets was 495 million tons of carbon dioxide equivalent, with a turnover of 11.978 billion yuan. The compliance rate of key emission units remained high. Furthermore, the total amount and intensity of carbon emissions within the market coverage have maintained a double downward trend, effectively promoting relevant enterprises to actively reduce GHG emissions. Nonetheless, is this in line with the inherent transformation of the enterprises themselves, or is it on the basis of the transfer of “carbon”? Further investigation is needed.

2.2 Theoretical hypothesis

2.2.1 Reducing the cost of carbon emissions

Since the connotation of regional carbon emission transfer is similar to carbon leakage, the carbon emission transfer can also be defined as the increase in emissions outside a region, as a direct result of the policy to cap emission in this region (Reinaud, 2008). There are three primary explanations for the formation mechanisms of carbon emission transfer. The first one is “free-rider leakage” (Carraro and Siniscalco, 1992). The second one is “supply side leakage” (Sinn, 2008).

The third one is “specialization leakage”. Siebert (1979) and Copeland and Taylor (2005) pointed out that to reduce carbon emissions, unilateral introduction of carbon prices in developed countries would shift comparative advantage towards developing countries without climate policy, and lead to increased production of carbon intensive goods in those countries. Further, Song et al. (2021) find that when different firms within an enterprise group face different emission rates, firms located in areas with high emission rates shift their production, especially pollution-intensive production, to firms in areas with low emission rates, which in turn leads to pollution transfer within the enterprise group. Based on the above discussion, this paper argues that after the implementation of carbon trading policy, enterprises can reduce their carbon emissions through technology upgrading, but this practice is risky and enterprises may suffer from the double costs of R&D expenditures and purchasing carbon emission rights. Firms are more likely to shift their carbon emissions considering the uncertainty of technological upgrading. Specifically, when enterprises upgrade their green technologies, they will inevitably bring about an increase in R&D costs, and on the other hand, they may face the double cost of having to pay for the purchase of carbon emission rights even after their R&D fails. Even if an enterprise succeeds in research and development and obtains proceeds from the sale of carbon emission rights, the research and development process costs a lot, and after deducting various costs such as research and development, the actual proceeds that an enterprise can obtain are relatively small. In particular, for companies with poor R&D capabilities, reducing carbon emissions through technological upgrades exacerbates corporate costs. Rational companies will choose a less costly way to reduce their carbon emissions, i.e., by shifting their carbon emissions to a different location by establishing a subsidiary in a different location. This approach allows companies to avoid the various costs associated with carbon trading policies and alleviates the pressure on the parent company to reduce emission.

2.2.2 Gains from transfers

Aside from cost drivers, there are also benefits to be gained from transferring “carbon” by establishing subsidiaries across regions. From the viewpoint of transaction costs, enterprises trading in off-site markets will bring about an increment in transaction costs (Cao et al., 2019). Establishing off-site subsidiaries not only expands the market scale of enterprises but also strengthens cooperation with off-site enterprises and curtails the transaction costs of parent companies in off-site locations. Aside from that, through the reasonable layout of the geographical location of subsidiaries, enterprises are able to directly allocate the resource endowment of off-site locations to lessen the cost of acquiring raw materials (Cao et al., 2015).

In summary, this paper holds a standpoint that when confronted with carbon trading policies, companies will choose to establish subsidiaries to transfer “carbon” to avoid the costs of carbon trading policies and obtain certain benefits.

3 Research design

3.1 Sample selection and data source

This paper selected the data of Chinese A-share listed companies in Shanghai and Shenzhen from 2009 to 2018 as the research object, and the firm-level data involved are predominantly from the Wind

and CSMAR databases. To effectively examine the impact of carbon trading policies on the off-site “carbon” transfer of enterprises, this paper has conducted some screening of the sample. First, since the carbon trading policy primarily affects high-carbon industries, the full sample regression will give rise to biased policy estimation. For this reason, according to the data collected by the World Resources Institute (WRI), the emissions from the power generation and heating industry account for 41.6% of China’s total carbon emissions. Meanwhile, this paper draws lessons from [Zhang and Wu \(2022\)](#) to select extractive industries (B), manufacturing industries (C), and electricity, gas and water production and supply industries (D) as high-carbon industries as the predominant objects of investigation in accordance with the Industry Classification Guidelines for Listed Companies issued by the China Securities Regulatory Commission in 2012. Second, to avoid the impact of outliers on the regression, a 1% reduction in the continuous variables was conducted in this paper. Third, financial data outliers were excluded. Fourth, the sample whose parent company had migrated out of the original province from 2009 to 2018 was excluded.

3.2 Model

In this paper, we used the carbon trading pilot implemented in 2013 as a quasi-natural experiment to explore the impact of carbon trading policies on the behaviors of high-carbon firms in shifting “carbon” emissions using the Difference-in-Differences approach (DID). As Shenzhen belongs to Guangdong, for this reason the experimental group of this paper is Beijing, Tianjin, Shanghai, Chongqing, Guangdong, Hubei six provinces and cities, while Fujian Province joined the pilot in 2016. To avoid estimation bias, this paper will remove the sample of enterprises in Fujian Province. The other 25 provinces will be employed as the control group. The dummy variable *Treat* is whether the province is a pilot province for carbon emissions trading; in the event that the province is a pilot province for carbon emissions trading, then *Treat* = 1; conversely, providing that the province does not obtain pilot carbon emissions trading, then *Treat* = 0. The dummy variable *period* is the year in which pilot carbon emissions trading starts; in the event that it is in 2013 and later, then *period* = 1; conversely, before 2013, then *period* = 0. The model is constructed as follows.

$$Sub\_Nub_{jt} = \alpha_0 + \beta_1 did_{jt} + \gamma_1 X_{jt} + \delta_j + \theta_t + \varepsilon_{ijt} \quad (1)$$

where *Sub_Nub_{jt}* is the explained variable of this paper, which indicates the number of off-site subsidiaries of enterprise *j* in period *t*. *did_{jt}* is the core explanatory variable of this paper, which is the interaction term of dummy variables *Treat_i* and *period_t*, which indicates whether province *i* is approved as a carbon emission trading pilot in period *t*. *X_{jt}* are firm-level control variables, chiefly including firm size, firm listing period, profitability, cash holding level, firm leverage level, etc.; δ_j are firm fixed effects; θ_t are time fixed effects; ε_{ijt} are random error terms. β_1 The coefficient indicates the net effect of carbon trading rights on the transfer of “carbon” across dissimilar locations, and when the coefficient β_1 is significantly >0, carbon trading policies promote the transfer of “carbon” from high-carbon companies to other locations.

3.3 Variable definition

3.3.1 Explained variable

Enterprise off-site transfer of “carbon” behavior: *Sub_Nub_{jt}*. In this paper, we employ the number of off-site subsidiaries of enterprise *j* in period *t* to measure the off-site transfer of “carbon” by enterprises. In the event that the newly established subsidiaries of the parent company of the experimental group are all in the experimental group of the remaining provinces, this will inevitably result in biased policy estimates in the policy assessment. As a result, to obtain the net effect of carbon trading policy on the cross-regional “carbon” transfer of enterprises, this paper excludes the newly established subsidiaries of parent companies located in the experimental group provinces in the remaining experimental group provinces.

3.3.2 Explanatory variable

The explanatory variable: *did_{jt}*, which is the interaction term of dummy variables *Treat_i* and *period_t*, which indicates whether province *i* is approved as a carbon emission trading pilot in period *t*. The dummy variable *Treat* is whether the province is a pilot province for carbon emissions trading; in the event that the province is a pilot province for carbon emissions trading, then *Treat* = 1; conversely, providing that the province does not obtain pilot carbon emissions trading, then *Treat* = 0. The dummy variable *period* is the year in which pilot carbon emissions trading starts; in the event that it is in 2013 and later, then *period* = 1; conversely, before 2013, then *period* = 0.

3.3.3 Control variables

Apart from implementing carbon trading policies on enterprises’ transfer of “carbon” across regions, some factors at the enterprise level will also affect the transfer behavior of “carbon”, and the following control variables will be selected in this paper. (i) Firm size (*size*), expressed as the logarithm of the firm’s total assets. (ii) Year in which the company was listed (*lnage*) by subtracting the logarithm of the year in which it was listed from the current year. (iii) Corporate profitability (*ROA*), expressed as net profit margin on total assets. (iv) Cash holdings (*CASH*), cash holdings = (monetary funds + financial assets held for trading)/total assets. (v) leverage (*leverage*), measured by the firm’s gearing ratio. (vi) Noncurrent assets ratio (*non_AS*), expressed as the ratio of noncurrent assets to total assets. Descriptive statistics for the chief variables are given in [Table 1](#).

3.3.4 Characteristic fact analysis

Before conducting the empirical analysis, this paper conducted a characteristic factual analysis of the trend of carbon emissions per firm in the experimental and control groups. The current energy mix in China is dominated by coal and oil consumption, accounting for 56% and 18.5% of total energy consumption, respectively, or a combined 74.5% (data from the National Bureau of Statistics 2021). For this reason, this paper fixes its attention on the amount of carbon dioxide produced by enterprises consuming coal and oil, where enterprise unit carbon emissions = total carbon emissions from coal and oil/total number of enterprises. As apparently revealed in the graph, in 2015, the carbon emissions per unit of relevant enterprises in the control group are progressively rising, and there is a lag of “carbon” migration. This is a preliminary reflection of the fact that enterprises are moving carbon. As in [Figure 1](#).

TABLE1 Descriptive statistics.

Variable name	Abbreviations	Definitions	Measurement	N	Mean	SD
Explained variable	Sub_Nub	Transfer “carbon” behavior	The number of subsidiaries in different provinces	13353	5.87	8.84
Explanatory variable	did	Whether it is approved as a pilot carbon emission trading scheme	Is the interaction item of dummy variables Treat and Period	13353	0.23	0.42
Control variable	size	Company size	Expressed as the logarithm of the total assets of the business	13353	22.13	1.27
	lnage	The age at which the business went public	Expressed as the logarithm of the current year minus the year of listing	13353	2.08	0.85
	roa	Enterprise profitability analysis	Expressed in terms of net profit rate on total assets	13353	0.03	0.059
	cash	Cash holdings	(Monetary funds + trading financial assets)/Total assets	13353	0.16	0.11
	leverage	Lever ratio	Measured by enterprise asset-liability ratio	13353	15.91	24.71
	non_AS	Proportion of non-current assets	Expressed as the ratio of non-current assets to total assets	13353	0.46	0.18

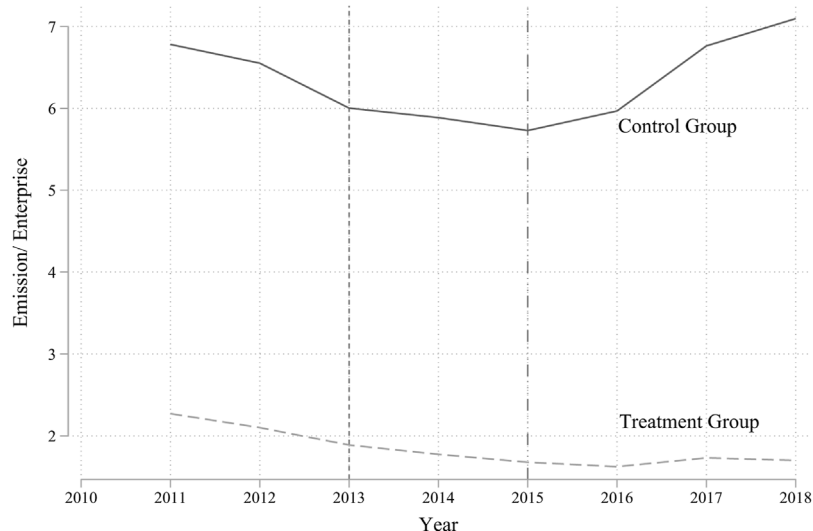


FIGURE 1
Facts about the characteristics of “carbon” migration of enterprises.

4 Empirical testing and result analysis

4.1 Baseline regression

This paper empirically examines the association between carbon trading policies and enterprises’ off-site transfer of “carbon” behavior on the basis of model (1). To prevent the omission of firm-level factors that do not vary over time from biasing the regression results, firm fixed effects are included in all regressions; to exclude the effect of factors associated with year characteristics, all regression results include time fixed effects. The regression results are exhibited in Table 2, where column (1) does not include control variables. As demonstrated by the research findings, carbon trading policies significantly drive the transfer of “carbon” from high-carbon firms in China. In column (2), the coefficient is still noticeably positive after

adding further control variables. The above results tentatively confirm the impact of carbon trading policy on the transfer of “carbon” by enterprises across regions.

4.2 Robustness test

4.2.1 Parallel trend test

In the benchmark regression analysis, this paper identifies the causal effect of carbon trading policy on the cross-regional transfer of “carbon” behavior of high-carbon firms in China, but this requires a DID parallel trend test to verify the validity of these results. In accordance with this, this paper draws on Beck et al. (2010) for a parallel trend test. Figure 2 shows the parallel trend results of the Difference-in-Differences model of this paper. The findings of this

TABLE 2 Baseline regression.

Variables	DID	DID
	(1)	(2)
	Sub_Nub	Sub_Nub
did	1.759*** (3.04)	1.586*** (2.84)
Constant	5.781*** (41.34)	-83.082*** (-6.19)
Observations	13,114	13,114
Adj R-2	0.698	0.721
Enterprise Fix effect	Yes	Yes
Time Fix effect	Yes	Yes
Regional fixed effect	No	No
Control variables	No	Yes

Note: Robust standard errors are reported in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

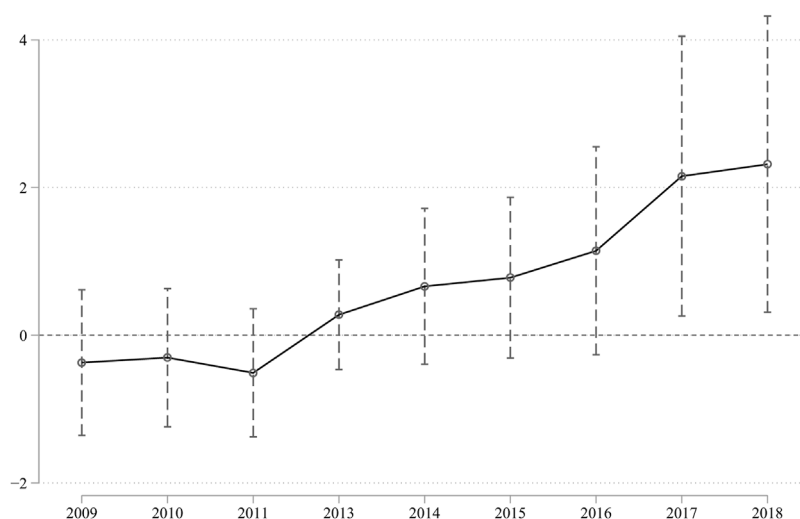


FIGURE 2
Parallel trend test.

paper pass the parallel trend test, and the impact of carbon trading policy on the cross-regional transfer of “carbon” behavior of high-carbon enterprises in China has progressively elevated after implementing carbon trading policies.

4.2.2 Placebo test

To further ensure the validity of the regression results, a placebo test with experimental group randomization was adopted to verify the robustness of the results. Randomizing the experimental group is a random sampling of the experimental group variables a certain number of times, and then observing whether the coefficients of the randomized DID are concentrated approximately 0 and whether the coefficients significantly deviate from their true values. In this paper, by using a placebo test with 500 random samples of the

interaction term and plotting the distribution of regression coefficients (Figure 3), the majority of coefficients are concentrated approximately 0 and normally distributed, and the mean value is far from the true value, which means that the effect of carbon emissions trading policy on the transfer of “carbon” by enterprises across regions is not influenced by other unobserved factors and satisfies the placebo test.

4.2.3 PSM-DID

To better select the control group, this paper further adopts the propensity score matching method to test the causal correlation between carbon trading policy and the cross-regional transfer of “carbon” behavior of enterprises under other similar conditions. In this paper, we build a logit model for whether it is a carbon trading policy region, match Chinese provinces using the nearest 1:

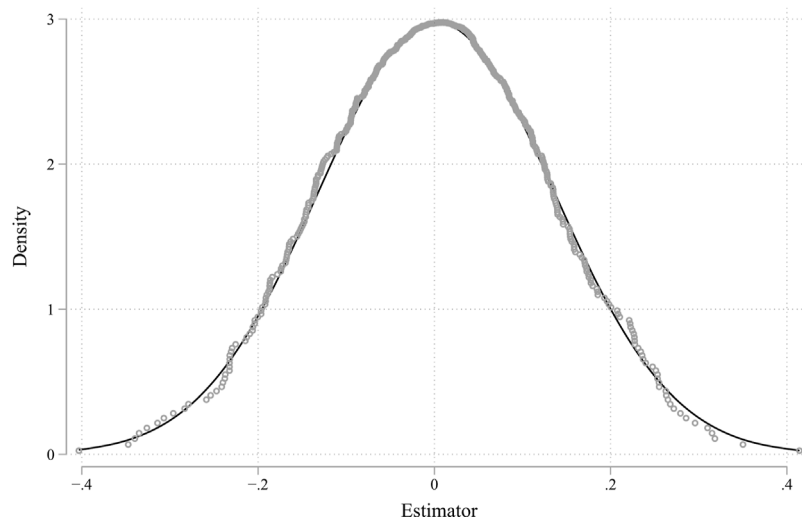


FIGURE 3
Placebo test.

TABLE 3 Robustness test.

Variables	PSM-DID	Eliminate other policy	Economic development level	Add area labor income	Add regional fixed effect
did	1.693*** (2.66)	1.616*** (2.88)	1.620*** (2.90)	1.347*** (2.76)	1.347*** (2.76)
Didm		-0.065 (-0.16)			
PerGDP			-0.101 (-0.10)	-1.344 (-0.71)	
Lincome				1.175 (0.66)	
Constant	-88.090*** (-9.10)	-81.651*** (-11.46)	-80.636*** (-6.14)	-75.177*** (-4.78)	-75.177*** (-4.78)
N	6,054	13,554	13,554	11,503	11,503
R-squared	0.730	0.720	0.720	0.734	0.733
Enterprise Fix effect	Yes	Yes	Yes	Yes	Yes
Time Fix effect	Yes	Yes	Yes	Yes	Yes
Regional fixed effect	No	No	No	No	Yes
Control variables	Yes	Yes	Yes	Yes	Yes

Note: Robust standard errors are reported in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

1 matching, and then employ the matched sample for regression. The estimation results of PSM-DID were obtained as illustrated in Table 3. As illustrated by the research findings obtained from Table 3, the estimated coefficient of the PSM-DID model is noticeably positive, and the magnitude of the coefficient is 1.693, which is approximately the same as the baseline estimation result of 1.586. The above analysis shows that endogeneity is mitigated to some extent by PSM-DID, and

the results are roughly the same as the benchmark results, i.e., carbon trading policies promote the “carbon” transfer of enterprises across regions.

4.2.4 Eliminate other policy interference

By combining relevant documents, it is found that the Green Credit Guidelines may interfere with the results of this paper during

TABLE 4 Mechanism analysis.

Variables	(1)	(2)	(3)	(4)
	Expenses	Revenues	R&D revenue	Operating income
did	1.581*	1.182	-5.140	
	(1.89)	(0.92)	(-0.96)	
				0.002***
Sub_Nub				(2.72)
Constant	13.854*	-57.871***	-74.567	3.527***
	(1.89)	(-4.77)	(-1.20)	(5.49)
Observations	13,099	13,082	10,046	13,109
Adj R-2	0.393	0.468	0.116	0.956
Enterprise Fix effect	Yes	Yes	Yes	Yes
Time Fix effect	Yes	Yes	Yes	Yes
Control variables	Yes	Yes	Yes	Yes

Note: Clustered robust standard errors are reported in parentheses below the coefficients. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Control variables are estimated as in the [Table 2](#) benchmark.

the sample period. For reference to the practice of [Fan and Li \(2022\)](#), this paper adds the Didm variable, $Didm = Time * Post$, into the benchmark regression. Where Time is the dummy variable of the year. If the number of years is greater than or equal to 2012, $Time = 1$; otherwise, $Time = 0$. Post is the dummy variable of a high-polluting enterprise. $Post = 1$ when it is a high-polluting enterprise; otherwise, $Post = 0$. The estimated results are shown in column (2) of [Table 3](#). When Didm is added, the estimated coefficient is still significantly negative at the 1% level. After removing the interference of green credit policies, the results remain robust.

4.2.5 Add province control variables

Since the characteristic variables at the provincial level may cause bias in the estimation results, this paper further adds the control variables at the provincial level, and the results are shown in [Table 3](#). The variable of the *per capita* GDP coefficient (PerGDP) of each region was added into column (3) of [Table 3](#), and the estimated coefficient of DID was still significantly positive at the 1% level. In addition, since regional labor income is an important factor affecting enterprise relocation, the variables of regional labor income (Lincome) are added into column (4) of [Table 3](#), and it can be seen that the coefficient of did is still significantly positive at the 1% level. Finally, the regional fixed effect was further added into column (5), and the regional-level characteristic variables were further controlled to alleviate the interference of regional-level characteristic variables on the results. After the provincial fixed effect was added, the DID coefficient was still significantly positive.

4.3 Analysis of the impact mechanism

As suggested by the above analysis, carbon trading policies have prompted high-carbon emitting enterprises to transfer “carbon” across regions. Nevertheless, the mechanisms involved still remains unclear and will be explored in this subsection.

4.3.1 Impact of carbon trading on business costs

On the basis of the Interim Regulations on Accounting Treatment of Carbon Emission Trading issued by the Ministry of Finance, the carbon emission allowances sold and purchased by enterprises are recorded as “nonoperating income” and “nonoperating expense”, respectively; as a consequence, this paper will examine the impact of carbon trading policy on the nonoperating expense and nonoperating income of enterprises to examine the impact on enterprise cost. The results are displayed in [Table 4](#). The coefficient of carbon trading policy on nonoperating expenses is remarkably positive, which means that carbon trading policy elevates the costs incurred by enterprises in the process of carbon trading (including the cost of purchasing carbon emission rights and the cost of participating in carbon emission rights trading). Column (2) of [Table 4](#) examines the proceeds obtained by the sale of carbon emission rights by enterprises with lower than the required carbon emissions after implementing the carbon trading policies. As demonstrated in [Table 4](#), the coefficient of (2) is positive but not significant, i.e., enterprises with lower than the required carbon emissions do not obtain corresponding returns from carbon emission rights trading. This is because, despite the fact that companies can gain from the sale of carbon credits, they also incur certain transaction costs during the sale process, and when carbon trading is first implemented, it's essential for companies to bear higher labor and material costs for preparation, which to some extent offsets the gains from the sale of carbon credits. As clearly revealed by the above results, the cost impact of carbon trading policy in the initial stage exceeds its benefit impact. Under such circumstance, rational companies will take initiatives to shift “carbon” to avoid the cost of carbon trading.

4.3.2 Analysis of R&D revenue

Second, this paper further examines the analysis of R&D benefits after implementing the carbon emissions trading policies, in which the explained variable is green technology R&D benefits (efficient), $efficient = nonoperating\ income \setminus total\ R\&D\ amount$. The results are exhibited in column (3) of [Table 4](#), and it is easy to see that the DID

TABLE 5 Corporate R&D capabilities.

Variables	(1)	(2)
	Weak R&D	Strong R&D
	Sub_Nub	Sub_Nub
did	0.928*	1.510
	(1.94)	(0.96)
Constant	−81.368***	−145.340***
	(−5.85)	(−3.18)
Observations	11,181	1,604
Adj R-2	0.734	0.812
Enterprise Fix effect	Yes	Yes
Time Fix effect	Yes	Yes
Control variables	Yes	Yes

Note: Clustered robust standard errors are reported in parentheses below the coefficients. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Control variables are estimated as in the [Table 2](#) benchmark.

TABLE 6 Alternative energy response of enterprises to the policy.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	Alternative Energy = 0	Alternative Energy = 1	Energy saving = 0	Energy saving = 1	Nuclear Energy = 0	Nuclear Energy = 1
	Sub_Nub	Sub_Nub	Sub_Nub	Sub_Nub	Sub_Nub	Sub_Nub
did	1.199**	0.279	1.472***	1.335	1.652***	−0.429
	(2.54)	(0.14)	(2.64)	(0.66)	(2.90)	(−0.34)
Constant	−77.868***	−219.242***	−80.200***	−138.287***	−82.254***	−117.486
	(−5.86)	(−3.02)	(−5.74)	(−3.11)	(−6.04)	(−1.41)
Observations	12,339	606	12,179	786	12,896	209
Adj R-2	0.732	0.855	0.721	0.821	0.722	0.531
Enterprise Fix effect	Yes	Yes	Yes	Yes	Yes	Yes
Time Fix effect	Yes	Yes	Yes	Yes	Yes	Yes
Control variables	Yes	Yes	Yes	Yes	Yes	Yes

Note: Clustered robust standard errors are reported in parentheses below the coefficients. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Control variables are estimated as in the [Table 2](#) benchmark.

coefficient is insignificant, i.e., the enterprises have not gained the benefits of technological upgrading temporarily after implementing the carbon trading policies. This is because when enterprises upgrade their green technology, on the one hand, it will inevitably bring an augment in R&D costs, and on the other hand, they may face the dual cost of purchasing carbon emission rights even providing that the R&D fails. Even if an enterprise succeeds in R&D and obtains the proceeds from the sale of carbon emission rights, the R&D process still costs a lot. What's more, the real proceeds that can be obtained are relatively small after deducting the R&D costs. For enterprises with relatively poor R&D capabilities, it would be more in their interest to avoid the above-mentioned dual costs by expending the dual costs of facing possible R&D expenses and purchasing carbon emission rights to obtain a small gain from the sale of carbon emission rights by

shifting the high carbon emission sectors to an offsite location. In the following analysis of firm heterogeneity, [Tables 5, 6](#) similarly corroborate the above arguments.

4.3.3 Benefits of transferring carbon

Apart from being cost-driven, there are also certain benefits to be gained by establishing subsidiaries across regions. From the standpoint of transaction costs, a firm facing a foreign market will be accompanied by an augment in market transaction costs ([Cao et al., 2019](#)), and establishing a foreign subsidiary not only expands the market scale of that firm but also strengthens cooperation with foreign firms and lessens the transaction costs of the parent company in the foreign market. Apart from that, by rationalizing the geographical location of subsidiaries, companies are able to directly allocate off-site

resource endowments to curtail the cost of acquiring raw materials (Cao et al., 2015). To argue the above statement, this paper regresses the logarithm of the parent company's operating income on the heterogeneous subsidiaries. The results are displayed in column (4) of Table 4, and the coefficient of Sub_Nub is noticeably positive. From an economic point of view, the addition of a subsidiary in an offsite location by the parent company raises the parent company's operating income by 0.2%. This confirms that it is beneficial for a parent company to establish a subsidiary in a foreign location.

The cost–benefit analysis reveals that when confronted with carbon trading policies, companies are highly motivated to move their high carbon emitting sectors off-site to avoid the dual cost of having to pay for carbon emission rights even after facing R&D failures. Meanwhile, they are also able to obtain certain benefits by establishing off-site subsidiaries.

4.4 Enterprise heterogeneity analysis

4.4.1 Corporate R&D capability

The green technology innovation ability of diverse enterprises will differ tremendously. Aside from that, this difference will affect the transfer of “carbon” across regions to a certain extent. For this reason, this paper measures the green technology innovation capability of enterprises by the number of green invention authorizations of listed companies and divides the full sample into two groups in accordance with whether the enterprises have green invention authorizations. Table 5 shows the results of the subsample regressions. As clearly revealed in Table 5, the carbon trading policy does not give rise to the transfer of “carbon” across regions when enterprises have strong R&D capability in green technology. This is because companies are able to cut down “carbon” emissions through R&D. When companies are less able to innovate in green technology, carbon trading policies will immensely facilitate the transfer of “carbon” from companies to ease the pressure of carbon emissions from parent companies.

4.4.2 Alternative energy response to policy

When a company has a new alternative energy source or the company consumes less energy, the company's carbon emissions will also be lessened on that account. Under this circumstance, such companies will benefit from the carbon trading policy. As a result, such companies will be less likely to migrate “carbon”. To test the above conjecture, this paper further subdivides green technology innovation into three groups: whether the company possesses the licensed amount of alternative energy inventions, energy-saving inventions, core power generation inventions, respectively. The regression results are displayed in Table 6, in column (1) (2) of Table 6. What's more, and the DID coefficient is strikingly positive when the firm has no alternative energy inventions and insignificant when the firm has alternative energy inventions. As displayed in Columns (3) and (4), the carbon trading policy does not affect the transfer of “carbon” when the company has an energy-saving invention. Nevertheless, when the company does not have a license for an energy-saving invention, the carbon trading policy will bring higher costs to the company, and the company will avoid it by transferring “carbon”. Finally, as exhibited in Columns (5) and (6), when a firm has clean nuclear energy to generate electricity, the firm's carbon emissions are bound to be lower, and the firm will be able to sell carbon emission rights in the carbon trading market, thus gaining

revenue. To put it in another way, the carbon trading policy will not affect the enterprises that own clean energy.

4.4.3 Response of firm size to policy

In this section, we further analyze the impact of the difference in enterprise size on the transfer of “carbon” from enterprises. On the contrary, small enterprises are less likely to shift their carbon emissions. To test the above arguments, this paper divided firms into larger and smaller firms by the median of their total assets and examines their responses to the policy separately. The results are exhibited in column (1) (2) of Table 7, from which it can be seen that the DID coefficient for large firms is markedly positive, while the DID coefficient for small firms is not significant, i.e., confirming the above conjecture.

4.5 The location of the carbon transfer distribution

This paper further divides the geographical location of “carbon” transfer into two groups, domestic and foreign, and examines the distribution location of “carbon” transfer of enterprises. The results are exhibited in Table 7. As exhibited in columns (3) and (4) of Table 7, the DID coefficients are both remarkably positive, but the coefficient of group (2) is larger and passes the empirical p-test, i.e., the companies are more inclined to transfer “carbon” domestically owing to the influence of carbon trading policies. This is because it is easier and less costly to establish a subsidiary in China than abroad, and it also requires a higher level of expertise, i.e., a higher threshold for the transfer of “carbon” in a foreign country.

4.6 The consequences of the transfer of a subsidiary company

Finally, this paper verifies whether the establishment of subsidiaries in different places will lead to the transfer of carbon emissions. At present, China's energy structure is mainly dominated by coal and oil consumption, which account for 56% and 18.5% of the total energy consumption, respectively, totalling 74.5% (data from the 2021 National Bureau of Statistics). To this end, this paper mainly investigates the carbon dioxide produced by the consumption of coal and oil by enterprises, and the results are shown in Table 8. Columns (1) and (2) in Table 8 investigate the CO₂ produced by coal consumption by carbon trading policies in various regions. The DID coefficient in column (1) is significantly negative; that is, carbon trading policies significantly reduce the CO₂ produced by coal. In column (2), add the Number (Number) of subsidiaries established across provinces by enterprises in different regions, whose coefficient is significantly negative and the DID coefficient decreases. This indicates that the establishment of subsidiaries in different places transfers carbon emissions to a certain extent. Similarly, columns (3) and (4) examined the effect of carbon trading policy on the amount of CO₂ produced by oil consumption, and the DID coefficient was still significantly negative. After adding the “Number” variable, the size of the DID coefficient decreased, and “Number” was significantly negative, which further indicated that the enterprise transferred carbon emissions by establishing remote subsidiaries. Finally, in columns (5) and (6), *per capita* carbon emissions were investigated. The DID coefficient was significantly negative, and the DID coefficient decreased after adding

TABLE 7 Analysis of firm size response to policy.

Variables	(1)	(2)	(3)	(4)
	Large scale	Small size	Foreign	Domestic
	Sub_Nub	Sub_Nub	Sub_Nub	Sub_Nub
did	3.650***	-0.063	0.393**	1.194**
	(3.07)	(-0.28)	(2.04)	(2.23)
Constant	-153.335***	-39.781***	-26.040***	-57.398***
	(-5.37)	(-3.26)	(-6.32)	(-7.34)
Observations	6,465	6,351	13,114	13,114
Adj R-2	0.741	0.712	0.663	0.688
Enterprise Fix effect	Yes	Yes	Yes	Yes
Time Fix effect	Yes	Yes	Yes	Yes
Control variables	Yes	Yes	Yes	Yes
Empirical <i>p</i> -values			0.00***	

Note: Clustered robust standard errors are reported in parentheses below the coefficients. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Control variables are estimated as in the Table 2 benchmark.

TABLE 8 Impact of carbon transfer on regional carbon emissions.

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
	Coal	Coal	Petroleum	Petroleum	Per capita carbon emissions	Per capita carbon emissions
did	-0.302***	-0.257***	-0.212***	-0.122***	-1.570***	-1.512***
	(-15.40)	(-21.56)	(-10.49)	(-8.77)	(-21.08)	(-27.03)
Number		-0.011***		-0.020***		-0.014*
		(-5.44)		(-4.16)		(-1.67)
Constant	10.295***	10.216***	9.357***	9.229***	10.857***	9.865***
	(52.90)	(52.49)	(31.26)	(31.67)	(9.46)	(50.97)
Observations	13,496	13,496	12,921	12,921	13,496	13,496
Adjusted R-squared	0.953	0.953	0.892	0.893	0.959	0.959
Enterprise Fix effect	Yes	Yes	Yes	Yes	Yes	Yes
Time Fix effect	Yes	Yes	Yes	Yes	Yes	Yes

Note: Clustered robust standard errors are reported in parentheses below the coefficients. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Control variables are estimated as in the Table 2 benchmark.

Number. Through the above tests, it is confirmed that the enterprise transfers carbon emissions by establishing subsidiaries.

5 Conclusion

In this paper, the carbon emissions trading pilot in China in 2013 is treated as a quasi-natural experiment to examine the transfer of “carbon” from high-carbon enterprises using data from A-share listed companies from 2009 to 2018 using a Difference-in-Differences method. As revealed by the reach findings, (1) part of the effectiveness of “carbon reduction” by enterprises is achieved through the transfer of high “carbon” sectors. (2) As illustrated in mechanism analysis, when high-carbon firms face the

dual cost pressure of R&D expenditures and purchasing carbon trading rights, they will avoid the parent company’s pressure to cut down emissions by establishing subsidiaries. As revealed in heterogeneity analysis, (3) companies with stronger R&D capability and higher success rates are more willing to upgrade their technology to cope with the impact of carbon trading policy. Companies with weaker R&D capabilities and higher failure rates are more likely to transfer carbon to avoid the “dual cost” of R&D failures. (4) Owing to the constraint of the migration threshold, the trajectory of “carbon” transfer is primarily domestic interregional transfer supplemented by cross-country transfer. (5) Larger enterprises emit more “carbon”, are more likely to pay more “carbon” reduction costs in the face of carbon policy shocks and are more likely to shift “carbon”.

This paper offers multiple policy insights as follows. (1) Ex post facto subsidies for green technology R&D innovation to guide enterprises with weak R&D capability to progressively withdraw from the market. When enterprises upgrade their green technologies, on the one hand, they will certainly bring an increment in R&D costs, and on the other hand, they may face the pressure of “dual costs” when they still need to pay for the purchase of carbon emission rights after their R&D fails. This reinforces the transfer of “carbon” from enterprises with higher carbon emissions and weaker R&D capabilities. This requires law enforcers to ameliorate environmental enforcement and at the same time to do a good job of top-level design to progressively guide such enterprises out of the market. (2) Focused monitoring by region. The central government should strengthen the key monitoring of regions with more resource endowments and lower labor costs to avoid the dilemma of “polluting before getting rich” in such regions.

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.

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XL: conceptualization, methodology, resources. JL: writing–review draft preparation, data curation, data analysis. DF: supervision, data analysis.

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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Emission reduction with hybrid mechanisms in civil aviation: An evolutionary game approach

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With the rapid growth of the aviation industry, the issue of carbon emissions has become a substantial challenge for governments and airlines. This paper proposes a hybrid carbon emission reduction mechanism, including major airlines in the emission trading systems and implementing carbon tax for small and medium-sized airlines. First, a tripartite evolutionary game model is constructed to study strategic behaviors. Second, four scenarios of evolutionarily stable strategies (ESSs) are analyzed. Finally, the influencing parameters of players' strategy choices are analyzed through simulations. The results show that: 1) the steady development scenarios (1, 1, 1) can be reached under the appropriate conditions; 2) the parameters such as carbon allowances and carbon tax prices significantly influence the evolutionary trend of stakeholders' dynamic choices; 3) the implementation of a hybrid mechanism by the government could facilitate the choice of low carbon operation strategies for both types of airlines. Accordingly, a series of policy recommendations are proposed to promote carbon emission reduction in civil aviation. This study combines evolutionary game and scenario analysis methods in an attempt to provide a new perspective on carbon emission reduction governance, thereby promoting the effective development of carbon emission reduction in civil aviation in the future.

KEYWORDS

carbon emission reduction, civil aviation, hybrid mechanisms, tripartite evolutionary game, scenario analysis

1 Introduction

Three main contributions are made in this study. First, in terms of governance of reducing civil aviation's carbon emissions, it offers a new perspective. In contrast to previous studies focusing on carbon tax or carbon trading, this paper proposes a hybrid mechanism including both a carbon tax and carbon trading system. The evolution of strategic behavior of the government, major airlines, and small and medium-sized airlines is discussed in relation to carbon emission reductions in civil aviation. Second, in contrast to a traditional evolutionary game, this paper also incorporates the scenario analysis method to classify the evolution of carbon emission reduction in civil aviation into four different scenarios. It studies the dynamic strategic choices of the three participants in different scenarios and the ESSs of the system. Third, this paper also attempts to analyze the key parameters influence game players' strategy choices, and proposes effective measures and recommendations that can guide the development of a hybrid mechanism for carbon emission reduction.

Carbon emission reduction is a global concern (Davis et al., 2018). The transportation sector accounts for approximately 15% of total GHG emissions across all sectors (Hu et al., 2022). As an essential component of the transportation sector, air transport delivers easy access and generates

considerable financial benefits but also generates significant carbon emissions (Zhang J.J. et al., 2019). Carbon emissions from the aviation industry have been shown to have an increasingly negative impact on climate change in numerous studies, and one of the largest sources of emissions is the combustion of aviation fuel (Dessens et al., 2014). Currently, the world's airlines burn more than 5 million drums of jet fuel per day, accounting for an estimated 3% of global carbon emissions (Liu et al., 2020). Boeing forecasts that global aviation carbon emissions are expected to increase to 1.23–1.49 billion tons by 2025 (Liu et al., 2022). After a long period of exploration and breakthroughs, it is becoming increasingly difficult to reduce aircraft emissions through many technologies (Torenbeek, 2013). In June 2022, the International Air Transport Association (IATA) called on governments to urgently develop large-scale reduction measures to rapidly expand the use of sustainable aviation fuel (SAF) so that the aviation industry can satisfy its pledge to achieve “zero” carbon emissions by 2050 (IATA, 2022). Therefore, in order to address these environmental threats, aviation carbon emission reduction must be undertaken rapidly.

To address the challenge of carbon emission reduction in civil aviation, market-based tools are the preferred available tools. Current incentive tools for reducing emissions, the Coase theorem (carbon trading) and Pigouvian taxation (carbon tax), are regarded as the most effective market tools for reducing carbon emissions (Stavins, 2008).

Many studies have used carbon tax mechanisms to address carbon emissions from civil aviation, and many European Union (EU) member states have already taken action to impose a carbon tax (Hu X et al., 2020). Fukui and Miyoshi demonstrate that an aviation carbon tax will reduce long-term fuel consumption and carbon emissions based on data from the United States airline industry (Fukui and Miyoshi, 2017). However, tax policy is devised by national legislatures, and legislation is a symbol of national sovereignty, so a uniform carbon tax on an international scale is not feasible (Mandell, 2008; Goulder and Schein, 2013; Snyder, 2015). Therefore, it is difficult for the carbon tax to regulate the international market (Zhang et al., 2017), i.e., the carbon emissions of international airlines cannot be effectively limited. Carbon emission trading systems are widely used around the world. During the 2008 presidential campaign, the United States developed a Regional Greenhouse Gas Initiative. Among Asian countries, Japan imposed a carbon tax in Saitama in 2012 and introduced an emission trading system in Tokyo in 2010 (Dong et al., 2010), and South Korea enacted a carbon trading system in January 2015. An important carbon trading market in the world has been expanded to include international airline operations, namely, the European Union Emission Trading Scheme (EUETS), as stated in Decree 2008/101/EC issued in November 2008. ETSs play an important role in aviation carbon reduction. However, there concerns remain in the implementation of carbon trading. For example, an emission trading system is costly to implement relative to a carbon tax (Stavins, 2022), and incorporating all Major airlines and small-sized and medium airlines into a carbon trading system will undoubtedly dramatically increase costs.

Therefore, a more viable mechanism is needed to mitigate aviation carbon emissions. By examining the impact of the aviation carbon tax on the United States travel carbon emissions, Hofer et al. suggest that carbon tax can be used as a complementary tool in conjunction with carbon trading (Hofer et al., 2010). Therefore, a new hybrid mechanism combining carbon trading

and the carbon tax is established to explore a more suitable approach for overall civil aviation.

However, when it comes to carbon emission reduction in civil aviation, there is a conflict between the government and airlines, i.e., maximizing airline profits and implementing carbon reduction strategies cannot be achieved simultaneously. Therefore, an approach that successfully balances airline development and environmental protection is essential to resolving this conflict. In the face of a challenging civil aviation transport market and stringent conservation measures, airlines and governments need to discover a way to balance green and sustainable development. (Lu, 2009). The major airlines were included in the carbon trading, while small and medium-sized airlines were subject to the carbon tax (Xu et al., 2016). The government gives the major airlines initial free carbon allowance, giving them more economic benefits, while they can exchange carbon allowances in the carbon trading system. Small and medium-sized airlines must pay the government-mandated carbon tax, and since the excess is taxed at a substantially higher rate than their profits, implementing progressive taxation can effectively solve this problem (Oishi et al., 2012). In addition to government factors, public opinion in a competitive environment can also influence airlines' emissions reduction behavior. Several studies have found that companies' low-carbon decisions are driven by public opinion (Liu et al., 2012; Zhang et al., 2013). Based on the above discussion, the behavior exhibited by the government, major airlines, and small-sized and medium airlines represents an evolutionary game. Game theory can provide some interesting clues from the perspective of the interaction of players involved in civil aviation carbon emissions reduction. For example, Dixit et al. constructed a Bertrand duopoly game model between two airlines to explore the impact of the carbon tax on airlines' green investment decisions (Dixit et al., 2022). However, the existing studies do not consider the emission reduction behavior of the government and airlines under the hybrid mechanism.

To fill the deficiencies in the literature highlighted above, we established a tripartite evolutionary game model consisting of the government, major airlines, and small and medium-sized airlines to study the problem of carbon emission abatement in civil aviation. The following reasons make this approach an attractive choice for our research question: first, it is obvious that the regulation of carbon emission reduction in civil aviation is a dynamic process, and the government and airlines will choose the appropriate strategy according to the changes in revenue and expenses. Unlike traditional game theory, evolutionary games reach equilibrium dynamically (Shao and Yuan, 2022). Second, the government and airlines are limited rational. Evolutionary game theory is more realistic in terms of limited rationality (Zhang S et al., 2019). Third, evolutionary games are widely used in policy decision analysis and perform well (Wang et al., 2021). Recently, research on environmental issues and policy decisions has been conducted using evolutionary games. Consequently, the evolutionary game can be used to systematically address the dilemma of carbon emission reduction in civil aviation.

The remainder of the paper is structured as follows. An overview of the relevant literature for this study is presented in Section 2. An evolutionary game model is constructed in Section 3. The strategic stability and stability points of the evolutionary game model are analyzed in Section 4. The evolutionary process and the key

parameters affecting the model are introduced by numerical simulations in Section 5. Section 6 provides a discussion. Finally, Section 7 presents conclusions and policy insights.

2 Literature review

2.1 Carbon emission reduction mechanism

Civil aviation carbon reduction is a thorny issue for the government, major airlines, and small and medium-sized airlines. Most studies on environmental regulations involve carbon tax or carbon trading mechanisms. The carbon tax is a price tool that is equivalent to setting a price for each unit of carbon emissions, according to which enterprises adjust their carbon emission behavior. Emission trading is a quantitative tool that first defines a total carbon allowance and then issues allowances to companies based on their historical emissions or other methods, and their allowances can be traded in the market. Each approach has advantages and disadvantages (Stavins, 2022).

Zhang et al. comparatively analyze carbon tax and carbon trading from the perspectives of system cost, political feasibility, emission reduction effect, social efficiency (Zhang et al., 2017), and international cooperation and find that carbon tax and carbon trading have advantages and disadvantages and that the implementation of a hybrid system consisting of both should achieve complementary advantages. Vollebergh et al. note that a hybrid carbon tax and carbon trading mechanism can overcome political resistance without affecting firms' incentives to reduce emissions (Vollebergh et al., 1997). Zhao et al. find that carbon taxes and carbon trading form a policy mix that is comprehensive in terms of price flexibility and coverage (Zhao L et al., 2020). In addition, the cost of monitoring and enforcement will be substantially reduced due to the reduction in the number of participating companies. Lehmann et al. also highlight that having multiple factors under one emission reduction policy, for instance, the cost of abatement to firms and the consistency of policy implementation, may lead to increased transaction costs and that an appropriate hybrid of the two policies may yield a better result (Lehmann, 2012).

Academics have proposed several hybrid mechanisms. Pizer proposes a carbon trading with a carbon tax concept: when the price of carbon trading exceeds a pre-set level, manufacturers can purchase carbon allowances from the government at a constant level without restriction, thus ensuring that economic activities can still operate under the emission reduction policy (Pizer, 2002). Snyder proposes another hybrid system to control the cost of emissions, where carbon-emitting companies pay a fixed price for the carbon tax and the government make use of the carbon tax revenue to purchase allowances in the carbon market for enterprises to reduce emissions (Snyder, 2015). This hybrid mechanism is more conducive to incentivizing enterprises to adopt abatement strategies, and the government maintain firm control over the reduction targets. Mandell, (2008) extends Weitzman's (Weitzman, 1974) study by examining a system in which one sector implements carbon trading while another sector implements a carbon tax. The division of sectors is the result of a tradeoff between abatement efficiency and quantity, suggesting that such hybrid

mechanisms are often better than the isolated implementation of one mechanism. Chiu et al. (2015) designed a hybrid mechanism for estimating energy prices, and the results indicate that this mechanism is applicable to the gasoline market in Taiwan. Zhang et al., in a study of greenhouse gas emissions, show that hybrid mechanisms can help achieve peak carbon by 2030 and at a lower cost than a pure emission trading system (Zhang et al., 2022a). The advantages of hybrid mechanisms are increasingly being noted in studies. Cao et al. (2019), for instance, evaluate a hybrid mechanism and report that it achieved set targets while losing less carbon trading prices and GDP than the implementation of an emission trading system alone. Unlike Cao et al., Bi et al. contend that the effectiveness of the hybrid mechanism is not a straightforward mixture of a carbon tax and carbon trading but shows an alternative pathway to green development (Bi et al., 2019). All of the above studies on hybrid mechanisms have demonstrated their benefits in terms of emissions reduction, but few studies have applied hybrid mechanisms to the transport sector.

2.2 Evolutionary game analysis of emission reduction

In contrast to traditional approaches, which usually ignore social interactions when studying the behavior of players, game theory sets the theoretical basis for determining the strategies used to formulate choices in an environment where rational participants collaborate with each other (Eissa et al., 2021; Jiang et al., 2022). However, traditional game theory has certain shortcomings (Ji et al., 2019). First, it assumes that all players are "perfectly rationality", while this is rarely true in reality. Second, it supposes that all stakeholders have the same decision environment and level of rationality, which is not actually the case. Finally, traditional game theory is static and cannot dynamically describe changes in the strategic behavior of participants. Dixit et al. discuss the impact of carbon taxes on airlines' greening investment decisions, however, the use of evolutionary games may better describe the dynamic decision-making process of airlines (Dixit et al., 2022).

Evolutionary games are a refinement and extension of traditional games, addressing the constraints of traditional game theory (Friedman, 1998). Evolutionary games combine game theory and dynamic evolutionary processes, emphasizing dynamic processes rather than focusing on statics, and explaining the reasons and ways that players reach a stable state.

Evolutionary game theory has an undeniable advantage in regulating carbon emissions (Jiang et al., 2019; Wang et al., 2021). Jiang et al. study the dynamics of players' decisions to reconcile the conflicting interests between the governments and shipping companies to better the environment in coastline areas. This plays a crucial part in the emissions abatement behavior of governments and maritime enterprises, as well as in policy development (Jiang et al., 2020). Chong and Sun note that evolutionary game theory is a powerful tool that could help the central government solve the twin dilemmas of environmental protection and economic growth (Chong and Sun, 2020). Similarly, Meng et al. analyzed the evolutionary path of the choice of emissions abatement strategies of the governments, port companies and maritime companies, and investigate the

mechanisms influencing the choices of players (Meng et al., 2022). Based on an evolutionary game, the above study analyzes only two or three parties' dynamic game relationships. However, no evolutionary game studies have emerged to address a hybrid emission reduction mechanism. Thus, this paper systematically and comprehensively investigates the mechanism of low-carbon behavior between the government and airlines under a hybrid mechanism.

Existing studies mainly cover carbon trading, carbon tax and SAF. This study combines carbon trading and carbon tax to construct a hybrid emission reduction mechanism and considers the airlines' implementation of emission reduction strategies combined with the introduction of SAF. Therefore, we have developed a tripartite evolutionary game model consisting of the government, major airlines, and small and medium-sized airlines to contribute to the current state of the civil aviation carbon reduction dilemma.

3 Evolutionary game model

3.1 Problem statement and model hypothesis

Civil aviation carbon emission reduction governance is a complicated system project for both international and national purposes, involving multiple interests, and its mechanism of action is complex and extensive. The government is the implementer of the policy, while the main target of the airlines is to control or minimize the emissions from the operation of the aircraft. The government allocates free carbon allowances to the major airlines, and if there are carbon allowances left in a cycle, the major airlines can sell the remaining carbon allowances; if the usage exceeds the carbon allowances, then major airlines need to purchase additional carbon allowances. The small and medium-sized airlines are subject to a carbon tax. The carbon tax is progressive, and a punitive carbon tax is payable when the threshold is exceeded (Qiu et al., 2020).

Based on the relevant theoretical and practical problems, the interaction between the government, major airlines, and small and medium-sized airlines is shown in Figure 1. Following the previous analysis, carbon emission reduction in civil aviation is a multistage and dynamic process. Therefore, this paper explores the dynamic evolutionary game of emission reduction in civil aviation from the perspective of a hybrid mechanism.

Before the evolutionary game model is constructed, several hypotheses are stated.

- (1) As shown in Table 1, all three players in the evolutionary game, the government, major airlines and small and medium-sized airlines, have two strategies. The results of their strategy choices evolve over time and stabilize at the optimal strategy. (Wang et al., 2022).
- (2) The three players are subject to asymmetric information. All players attempt to reduce carbon emissions while maximizing their own benefits. (Friedman, 1991).
- (3) One of the most effective options for significant reductions in carbon emissions in a relatively short time frame is to mix SAF

with traditional aviation fuel (TAF) (Heyne et al., 2021). Therefore, we assume that the only cost of both the major airlines and small and medium-sized airlines is for aviation fuel. The airlines use only SAF in the NO strategy and a mix of SAF and TAF in the AO strategy.

3.2 Parameters defining the construction of the payoff matrix

Major airlines parameter setting: The cost of the major airlines is C_{MY} and C_{MN} when the AO and NO strategies are adopted, respectively. Moreover, since a mixture of TAF and SAF ($P_{SAF} > P_{TAF}$) is required when adopting the AO strategy, $C_{MY} = SAF_{MY}P_{SAF} + TAF_{MY}P_{TAF}$ and $C_{MN} = SAF_{MN}P_{SAF} + TAF_{MN}P_{TAF}$, $C_{MY} > C_{MN}$, where SAF_{MY} and TAF_{MY} and SAF_{MN} and TAF_{MN} are the usages of SAF and TAF when the major airlines adopt the AO and the NO strategies, respectively. The comprehensive revenue in these two cases is denoted CP_{MY} and CP_{MN} , respectively, while when the major airlines adopt the AO strategy, $CP_{MY} > CP_{MN}$ because of the improved brand image, the government subsidies and the environmental benefits it brings (Zhang et al., 2022b). The carbon emissions are E_{MY} and E_{MN} , respectively. The government assigned cost-free carbon allowances for the major airlines representing Q_M , while the carbon emissions of the major airlines are E_{MY} and E_{MN} under different strategies ($E_{MY} < Q_M < E_{MN}$). In the emission trading system, carbon allowances are traded at price p . Therefore, the revenue from the sale of carbon allowances by the major airlines and the cost of purchasing carbon allowances are represented by $P_{MO} = p(Q_M - E_{MY})$ and $P_{MI} = p(E_{MN} - Q_M)$, respectively. In addition, based on empirical observation, we assume that $P_{MI} > P_{MO}$.

Small and medium-sized airlines parameter setting: Similarly, the costs are C_{SY} and C_{SN} when the small and medium-sized airlines adopt the AO and NO strategies, respectively, where $C_{SY} = SAF_{SY}P_{SAF} + TAF_{SY}P_{TAF}$, $C_{SN} = SAF_{SN}P_{SAF} + TAF_{SN}P_{TAF}$, and $C_{SY} > C_{SN}$. The comprehensive revenue in these two cases is denoted CP_{SY} and CP_{SN} , respectively. When the small and medium-sized airlines adopt the AO strategy, $CP_{SY} > CP_{SN}$ due to the improvement in brand image, the government subsidies and environmental benefits. The carbon emissions are E_{SY} and E_{SN} , respectively. The threshold for progressive taxation set by the government for the small and medium-sized airlines is E_S , so $E_{SY} < E_S < E_{SN}$ (Oishi et al., 2012). The punitive carbon tax price when the threshold is exceeded is denoted by t_N , and the regular carbon tax when the threshold is not exceeded is denoted by t_Y . Therefore, when the small and medium-sized airlines adopt the AO strategy, the carbon tax to be paid is $t_Y E_{SY}$, while the carbon tax to be paid when the NO strategy is adopted is $t_Y E_S + t_N (E_{SN} - E_S)$.

Government parameter setting: If the government adopts the AR strategy, the implementation of the emission trading system can yield carbon trading profits (trading fees, membership fees, etc.), θ is the trading factor (Fang et al., 2022), and θP_{MI} and θP_{MO} represent the government's profit from the carbon trading of the major airlines. If the government adopts the NR strategy, it will not obtain benefits from carbon trading, and the major airlines does not need to engage in carbon trading. When both the major airlines and small and medium-sized airlines adopt the AO strategy, the

government will receive additional benefits due to the significant governance effect, which is denoted U_{MSY} . When the government adopts the AR strategy, its control is denoted by C_{S1} , while the major airlines and small and medium-sized airlines will be constrained by the corresponding carbon emission reduction mechanism. The cost of the government when adopting the NR strategy is denoted by C_{S2} , and $C_{S2} < C_{S1}$ due to the reduction in human and material resources spent on the supervision of the major airlines and small and medium-sized airlines. The public opinion pressure (i.e., brand image) on the small and medium-sized airlines to adopt the NO strategy when the major airlines adopt the AO strategy is denoted by PO_{MS} , and the public opinion pressure on the major airlines to adopt the NO strategy when the small and medium-sized airlines adopt the AO strategy is denoted by PO_{SM} (Zhang et al., 2022a).

We used the “bottom-up” approach recommended by the International Civil Aviation Organization (ICAO) to calculate the emissions of small and medium-sized airlines and major airlines (ICAO, 2016). F_{ij} is the amount of fuel (kg) consumed by a type i aircraft in phase j ; j are five phases of aircraft operation, namely, takeoff, climb, approach, taxi (landing and takeoff (LTO) phase) and climb cruise descent (CCD) phase; R_{ij} is the fuel consumption rate ($\text{kg}\cdot\text{s}^{-1}$) of one engine of a type i aircraft in phase j ; N_i is the number of engines fitted to a type i aircraft; and T_{ij} is the standard duration (s) of a i aircraft in operation j . The ICAO gives the standard duration of each operational phase of the aircraft: Take-off, climb, approach and taxi times are 0.7 min, 2.2 min, 4 min and 26 min respectively (7 min for taxi-in and 19 min for taxi-out). Therefore, the equation for F_{ij} is $F_{ij} = \sum_j T_{i,j} \cdot R_{i,j} \cdot N_i$. E is the total fuel consumption (kg) for all phases of each type of aircraft. I is the CO2 emission parameter of aviation fuel ($\text{kg}\cdot\text{kg}^{-1}$). n_{ij} is the total number of i aircraft in j . Therefore, the total carbon emissions is $E = \sum_i F_i \cdot I \cdot n_{ij}$.

The relevant parameters of the model used in this study are shown in Table 2.

The evolution of carbon emission abatement can be regarded as a dynamic game among the major airlines, small and medium-sized airlines, and the government. The strategies of the airlines are AO and NO and those of the government are AR and NR. Based on the above hypotheses and parameters, the strategy combinations for the three players are obtained as follows.

$$\begin{aligned} (\Pi_{GO1}, \Pi_{MA1}, \Pi_{SA1}) &= (\theta P_{MO} + t_Y E_{SY} + U_{MSY} - C_{S1}, CP_{MY} \\ &\quad + P_{MO} - C_{MY}, CP_{SY} - C_{SY} - t_Y E_{SY}) \\ (\Pi_{GO2}, \Pi_{MA2}, \Pi_{SA2}) &= (\theta P_{MO} + t_Y E_S + t_N (E_{SN} - E_S) \\ &\quad - C_{S1}, CP_{MY} + P_{MO} - C_{MY}, CP_{SN} - C_{SN} \\ &\quad - t_Y E_S - t_N (E_{SN} - E_S) - PO_{MS}) \\ (\Pi_{GO3}, \Pi_{MA3}, \Pi_{SA3}) &= (\theta P_{MI} + t_Y E_{SY} - C_{S1}, CP_{MN} - P_{MI} \\ &\quad - C_{MN} - PO_{SM}, CP_{SY} - C_{SY} - t_Y E_{SY}) \\ (\Pi_{GO4}, \Pi_{MA4}, \Pi_{SA4}) &= (\theta P_{MI} + t_Y E_S + t_N (E_{SN} - E_S) \\ &\quad - C_{S1}, CP_{MN} - P_{MI} - C_{MN}, CP_{SN} - C_{SN} \\ &\quad - t_Y E_S - t_N (E_{SN} - E_S)) \end{aligned}$$

$$(\Pi_{GO5}, \Pi_{MA5}, \Pi_{SA5}) = (U_{MSY} - C_{S2}, CP_{MY} - C_{MY}, CP_{SY} - C_{SY})$$

$$(\Pi_{GO6}, \Pi_{MA6}, \Pi_{SA6}) = (-C_{S2}, CP_{MY} - C_{MY}, CP_{SN} - C_{SN} - PO_{MS})$$

$$(\Pi_{GO7}, \Pi_{MA7}, \Pi_{SA7}) = (-C_{S2}, CP_{MN} - C_{MN} - PO_{SM}, CP_{SY} - C_{SY})$$

$$(\Pi_{GO8}, \Pi_{MA8}, \Pi_{SA8}) = (-C_{S2}, CP_{MN} - C_{MN}, CP_{SN} - C_{SN})$$

The payment matrix constructed is shown in Table 3.

4 Model analysis

4.1 Strategy stability analysis for the government

Let U_1 and U_2 represent the expected benefit of the AR and NR strategies, respectively, for the government. According to Table 3, the government's game strategy is as follows.

$$U_1 = yz \Pi_{GO1} + (1-z)y \Pi_{GO2} + z(1-y) \Pi_{GO3} + (1-z)(1-y) \Pi_{GO4} \quad (1)$$

$$U_2 = yz \Pi_{GO5} + (1-z)y \Pi_{GO6} + z(1-y) \Pi_{GO7} + (1-z)(1-y) \Pi_{GO8} \quad (2)$$

The average profit of the government is indicated as $\bar{U}_{12}$ and is shown below.

$$\bar{U}_{12} = xU_1 + (1-x)U_2 \quad (3)$$

The consequent replicated dynamics equation is as follows (Friedman, 1991).

$$\begin{aligned} F(x) &= \frac{dx}{dt} = x(U_1 - \bar{U}_{12}) = x(1-x)(U_1 - U_2) \\ &= x(1-x)[t_N (E_{SN} - E_S) + t_Y E_S + \theta P_{MI} \\ &\quad + C_{S2} - C_{S1} - z[t_N (E_{SN} - E_S) + t_Y (E_S - E_{SY})] \\ &\quad - y\theta(P_{MI} - P_{MO})] \end{aligned} \quad (4)$$

According to the stability theorem for differential formulae (Jiang et al., 2019), $F(x)$ must be greater than 0 when the value of x is less than x^* . However, when x is greater than x^* , $F(x)$ is less than 0. Thus, to accomplish an ESS, $F(x) = 0$ and $F'(x) < 0$ are needed, as are $F(y)$ and $F(z)$. On the basis of this theory, the proposition is proposed as follow.

Proposition 1.

- (1) When $y = y^* = \frac{t_N (E_{SN} - E_S) + t_Y E_S + \theta P_{MI} + C_{S2} - C_{S1} - z[t_N (E_{SN} - E_S) + t_Y (E_S - E_{SY})]}{\theta(P_{MI} - P_{MO})}$, $F(x) \equiv 0$, and any value of x is an ESS of the government. The government's strategy does not change over time.
- (2) When $y \neq y^*$, assuming that $F(x) = 0$, then $x = 0$ and $x = 1$ are two stable points of x .

Proof of Proposition 1.

The derivative of the replicated dynamics equation of x can be calculated as follows:

$$\begin{aligned} F'(x) &= \frac{dF(x)}{dx} = (1-2x)[t_N (E_{SN} - E_S) + t_Y E_S + \theta P_{MI} \\ &\quad + C_{S2} - C_{S1} - z[t_N (E_{SN} - E_S) + t_Y (E_S - E_{SY})] \\ &\quad - y\theta(P_{MI} - P_{MO})] \end{aligned} \quad (5)$$

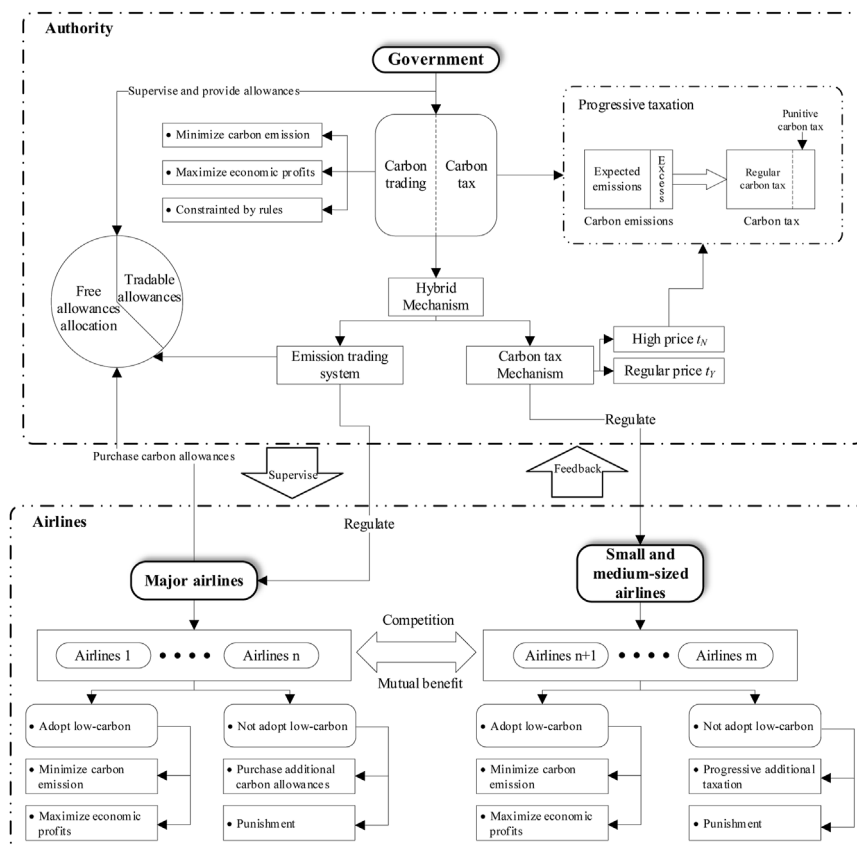


FIGURE 1
Interaction between multiple stakeholders.

Subsequently, two cases can be treated independently using Eq. 5.

i) If $t_N(E_{SN} - E_S) + t_Y E_S + \theta P_{MI} + C_{S2} - C_{S1} > \theta(P_{MI} - P_{MO}) + [t_N(E_{SN} - E_S) + t_Y(E_S - E_{SY})]$, under the conditions of x , y and $z \in [0, 1]$, it can be deduced that $t_N(E_{SN} - E_S) + t_Y E_S + \theta P_{MI} + C_{S2} - C_{S1} > y\theta(P_{MI} - P_{MO}) + z[t_N(E_{SN} - E_S) + t_Y(E_S - E_{SY})]$, i.e., $t_N(E_{SN} - E_S) + t_Y E_S + \theta P_{MI} + C_{S2} - C_{S1} - y\theta(P_{MI} - P_{MO}) - z[t_N(E_{SN} - E_S) + t_Y(E_S - E_{SY})] > 0$ is constant, $\frac{dF(x)}{dx}|_{x=0} > 0$ and $\frac{dF(x)}{dx}|_{x=1} < 0$. As a result, $x = 1$ is the ESS.

ii) If $t_N(E_{SN} - E_S) + t_Y E_S + \theta P_{MI} + C_{S2} - C_{S1} < \theta(P_{MI} - P_{MO}) + [t_N(E_{SN} - E_S) + t_Y(E_S - E_{SY})]$, then:

- ① When $y < y^*$, $\frac{dF(x)}{dx}|_{x=0} > 0$ and $\frac{dF(x)}{dx}|_{x=1} < 0$. Accordingly, $x = 1$ is the ESS.
- ② When $y > y^*$, $\frac{dF(x)}{dx}|_{x=0} < 0$ and $\frac{dF(x)}{dx}|_{x=1} > 0$. Accordingly, $x = 0$ is the ESS.

4.2 Strategy stability analysis for the major airlines

Suppose that the expected benefit when the major airlines adopt the AO strategy is U_3 , the expected benefit when the major airlines adopt the NO strategy is U_4 , and the average expected benefit is $\bar{U}_{34}$, we can obtain:

$$U_3 = zx \prod_{MA1} + (1-z)x \prod_{MA2} + z(1-x) \prod_{GO5} + (1-z)(1-x) \prod_{GO6} \quad (6)$$

$$U_4 = zx \prod_{MA3} + (1-z)x \prod_{MA4} + z(1-x) \prod_{MA7} + (1-z)(1-x) \prod_{MA8} \quad (7)$$

$$\bar{U}_{34} = yU_3 + (1-y)U_4 \quad (8)$$

Thus, the replicated dynamics equation of y is:

$$F(y) = \frac{dy}{dt} = y(U_3 - \bar{U}_{34}) = y(1-y)(U_3 - U_4) = y(1-y)[C_{MN} - C_{MY} - CP_{MN} + CP_{MY} + x(P_{MI} + P_{MO}) + zPO_{SM}] \quad (9)$$

Proposition 2.

- ① When $z = z^* = \frac{C_{MY} + CP_{MN} - CP_{MY} - C_{MN} - x(P_{MI} + P_{MO})}{PO_{SM}}$, $F(y) \equiv 0$, any value of y is an ESS for the major airlines. The major airlines' strategy does not change over time.
- ② When $z \neq z^*$, assuming that $F(y) = 0$, then y has two stable points at $y = 0$ and $y = 1$.

Proof of Proposition 2.

The derivative of $F(y)$ is given as below:

TABLE 1 Strategies for three players.

Players	Strategies
Government	Active regulate (AR)
	Negative regulate (NR)
Major airlines	Adopt low-carbon operation (AO)
	Not adopt low-carbon operation (NO)
Small and medium-sized airlines	Adopt low-carbon operation (AO)
	Not adopt low-carbon operation (NO)

$$F'(y) = \frac{dF(y)}{dy} = (1-2y)[C_{MN} - C_{MY} - CP_{MN} + CP_{MY} + x(P_{MI} + P_{MO}) + zPO_{SM}] \quad (10)$$

Then, two cases can be treated independently using Eq. 10:

i) If $C_{MN} - C_{MY} - CP_{MN} + CP_{MY} < -(P_{MI} + P_{MO} + PO_{SM})$, under the conditions of x, y and $z \in [0, 1]$, it can be deduced that $C_{MN} - C_{MY} - CP_{MN} + CP_{MY} + x(P_{MI} + P_{MO}) + zPO_{SM} < 0$ is constant, $\frac{dF(y)}{dy}|_{y=0} < 0$ and $\frac{dF(y)}{dy}|_{y=1} > 0$. Therefore, it is not difficult to obtain that $y = 0$ is the ESS.

ii) If $C_{MN} - C_{MY} - CP_{MN} + CP_{MY} + P_1 > -(P_{MI} + P_{MO} + PO_{SM})$, then:

- ① When $z < z^*$, $\frac{dF(y)}{dy}|_{y=0} < 0$ and $\frac{dF(y)}{dy}|_{y=1} > 0$. Accordingly, it is not difficult to obtain that $y = 0$ is the ESS.
- ② When $z > z^*$, $\frac{dF(y)}{dy}|_{y=0} > 0$ and $\frac{dF(y)}{dy}|_{y=1} < 0$. Accordingly, it is not difficult to obtain that $y = 1$ is the ESS.

4.3 Strategy stability analysis for the small and medium-sized airlines

Suppose that U_5 and U_6 are the benefits of the small and medium-sized airlines that select two strategies, i.e., the AO or NO strategy. $\bar{U}_{56}$ can represent the benefits of the small and medium-sized airlines that use the previous two strategies; then,

$$U_5 = yx\Pi_{SA1} + (1-y)x\Pi_{SA3} + y(1-x)\Pi_{SA5} + (1-y)(1-x)\Pi_{SA7} \quad (11)$$

$$U_6 = yx\Pi_{SA2} + (1-y)x\Pi_{SA4} + y(1-x)\Pi_{SA6} + (1-y)(1-x)\Pi_{SA8} \quad (12)$$

$$\bar{U}_{56} = zU_5 + (1-z)U_6 \quad (13)$$

Therefore, the replicated dynamics equation of z is as follows:

$$F(z) = \frac{dz}{dt} = z(U_5 - \bar{U}_{56}) = z(1-z)(U_5 - U_6) = z(1-z)\{CP_{SY} - CP_{SN} + C_{SN} - C_{SY} + x[t_N(E_{SN} - E_S) + t_Y(E_S - E_{SY})] + yPO_{MS}\} \quad (14)$$

Proposition 3.

- ① When $y = y^{**} = \frac{CP_{SN} - C_{SN} + C_{SY} - CP_{SY} - x[t_N(E_{SN} - E_S) + t_Y(E_S - E_{SY})]}{PO_{MS}}$, $F(z) \equiv 0$, any value of z is an ESS of the small and medium-sized airlines. The small and medium-sized airline's strategy does not change over time.
- ② When $y \neq y^{**}$, assuming that $F(z) = 0$, then z has two stable points at $z = 0$ and $z = 1$.

Proof of Proposition 3.

Similarly, the derivative of the replicated dynamics equation of z can be calculated as follows:

$$F'(z) = \frac{dF(z)}{dz} = (1-2z)\{CP_{SY} - CP_{SN} + C_{SN} - C_{SY} + x[t_N(E_{SN} - E_S) + t_Y(E_S - E_{SY})] + yPO_{MS}\} \quad (15)$$

Then, two cases can be treated independently using to Eq. 15:

- i) If $CP_{SY} - CP_{SN} + C_{SN} - C_{SY} < -[t_N(E_{SN} - E_S) + t_Y(E_S - E_{SY})] - PO_{MS}$, under the conditions of x, y and $z \in [0, 1]$, it can be deduced that $CP_{SY} - CP_{SN} + C_{SN} - C_{SY} + x[t_N(E_{SN} - E_S) + t_Y(E_S - E_{SY})] + yPO_{MS} < 0$ is constant, $\frac{dF(z)}{dz}|_{z=0} < 0$ and $\frac{dF(z)}{dz}|_{z=1} > 0$. Therefore, $z = 0$ is the ESS.
- ii) If $CP_{SY} - CP_{SN} + C_{SN} - C_{SY} > [t_N(E_{SN} - E_S) + t_Y(E_S - E_{SY})] - PO_{MS}$, then:

- ① When $y < y^{**}$, $\frac{dF(z)}{dz}|_{z=0} < 0$ and $\frac{dF(z)}{dz}|_{z=1} > 0$. Accordingly, it is not difficult to obtain that $z = 0$ is the ESS.
- ② When $y > y^{**}$, $\frac{dF(z)}{dz}|_{z=0} > 0$ and $\frac{dF(z)}{dz}|_{z=1} < 0$. Accordingly, it is not difficult to obtain that $z = 1$ is the ESS.

4.4 Stability analysis of equilibrium points

4.4.1 Equilibrium point

The following steps were taken to simplify the calculation process:

$$\begin{aligned} a &= t_N(E_{SN} - E_S) + t_Y E_S + \theta P_{MI} + C_{S2} - C_{S1}; \\ b &= t_N(E_{SN} - E_S) + t_Y(E_S - E_{SY}); \quad c = \theta(P_{MI} - P_{MO}); \\ d &= C_{MN} - C_{MY} - CP_{MN} + CP_{MY}; \quad e = P_{MI} + P_{MO}; \quad f = PO_{SM}; \\ g &= CP_{SY} - CP_{SN} + C_{SN} - C_{SY}; \quad h = PO_{MS} \end{aligned} \quad (16)$$

Substituting Eq. 16 into Eqs 4 and 9, 14, we obtain:

$$\begin{cases} F(x) = x(1-x)(a - bz - cy) \\ F(y) = y(1-y)(d + ex + fz) \\ F(z) = z(1-z)(g + hy + bx) \end{cases} \quad (17)$$

The simplified system of replicated dynamic equations, as shown in Eq. 17. When they are equal to 0, i.e., $F(x)$, $F(y)$, and $F(z) = 0$, we can obtain eight equilibrium points of pure strategies: $E_1(0, 0, 0)$, $E_2(1, 0, 0)$, $E_3(0, 1, 0)$, $E_4(0, 0, 1)$, $E_5(1, 1, 0)$, $E_6(1, 0, 1)$, $E_7(0, 1, 1)$, and $E_8(1, 1, 1)$. Except for E_1 to E_8 , there is also a hybrid-strategy equilibrium solution $E_9(x^*, y^*, z^*)$ that satisfies $F(x^*) = 0$, $F(y^*) = 0$ and $F(z^*) = 0$.

After obtaining the equilibrium point of the model, it is essential to analyze their stability and conditions for their

TABLE 2 Description of parameters in the evolutionary game model.

Major airlines	Description
Q_M	The cap of carbon allowances allocation
E_{MY}	The carbon emissions when the major airlines adopt the AO strategy
E_{MN}	The carbon emissions when the major airlines adopt the NO strategy, where $E_{MY} < Q_M < E_{MN}$
P_{MO}	The profits when the major airlines sell carbon allowances, where $P_{MO} = p (Q_M - E_{MY})$
P_{MI}	The cost of carbon allowances purchased by airlines when carbon emissions exceed the allocated carbon allowances, where $P_{MI} = p (E_{MN} - Q_M)$, $P_{MI} > P_{MO}$
CP_{MN}	The comprehensive revenue when the major airlines adopt the NO strategy
CP_{MY}	The comprehensive revenue when the major airlines adopt the AO strategy, where $CP_{MY} > CP_{MN}$
SAF_{MY}	The SAF usage when the major airlines adopt the AO strategy
TAF_{MY}	The TAF usage when the major airlines adopt the AO strategy
C_{MY}	The cost when the major airlines adopt the AO strategy, $C_{MY} = SAF_{MY}P_{SAF} + TAF_{MY}P_{TAF}$
C_{MN}	The cost when the major airlines adopt the NO strategy, $C_{MN} = SAF_{MN}P_{SAF} + TAF_{MN}P_{TAF}$, $C_{MY} > C_{MN}$
Small and medium-sized airlines	Description
CP_{SN}	The comprehensive revenue when the small and medium-sized airlines adopt the NO strategy
CP_{SY}	The comprehensive revenue when the small and medium-sized airlines adopt the AO strategy, $CP_{SY} > CP_{SN}$
E_S	The threshold of progressive taxation
E_{SY}	The carbon emissions when the small and medium-sized airlines adopt the AO strategy
E_{SN}	The carbon emissions when the small and medium-sized airlines adopt the NO strategy, $E_{SY} < E_S < E_{SN}$
SAF_{SY}	The SAF usage when the small and medium-sized airlines adopt the AO strategy
TAF_{SY}	The TAF usage when the small and medium-sized airlines adopt the AO strategy
C_{SY}	The cost when the small and medium-sized airlines adopt the AO strategy, $C_{SY} = SAF_{SY}P_{SAF} + TAF_{SY}P_{TAF}$
C_{SN}	The cost when the small and medium-sized airlines adopt the NO strategy, $C_{SN} = SAF_{SN}P_{SAF} + TAF_{SN}P_{TAF}$
Government	Description
U_{MSY}	The additional benefit to the government when the small and medium-sized airlines and major airlines adopt the AO strategy
C_{S1}	The government's cost when using the AR strategy
C_{S2}	The government's cost when using the NR strategy, $C_{S1} > C_{S2}$
PO_{MS}	The public opinion pressure (i.e., brand image) on the small and medium-sized airlines to adopt the NO strategy when the major airlines adopt the AO strategy
PO_{SM}	The public opinion pressure (i.e., brand image) on the major airlines to adopt the NO strategy when the small and medium-sized airlines adopt the AO strategy
Carbon tax	Description
t_Y	The regular carbon tax
t_N	The punitive carbon tax, $t_N > t_Y$
Emission trading	Description
θ	The trading factor
p	The carbon trading price
α	The emission parameter of traditional aviation fuel
β	The emission parameter of sustainable aviation fuel. ($\beta < \alpha$)
P_{SAF}	The sustainable aviation fuel (SAF) price

(Continued on following page)

TABLE 2 (Continued) Description of parameters in the evolutionary game model.

Major airlines	Description
P_{TAF}	The traditional aviation fuel (TAF) price
Carbon emission	Description
i	The parameter of aircraft types, where $i \in \mathfrak{R} = \{1, 2, \dots, K\}$
j	The five phases of aircraft operation; where $j \in \Psi = \{1, 2, \dots, 5\}$
R_{ij}	The fuel burn factor of one engine of a type i aircraft in phase j ($\text{kg}\cdot\text{s}^{-1}$)
N_i	The number of engines of i aircraft
T_{ij}	The standard time for i aircraft in j s, specially, $t_{CCD} = t_{TOTAL} - t_{LTO}$
I	The CO2 emission factor of fuel ($\text{kg}\cdot\text{kg}^{-1}$), where $I \in \mathcal{I} = \{\alpha, \beta\}$,
n_{ij}	The number of i aircraft in j
F_{ij}	The Fuel consumption of i aircraft in j ,
E	The total emissions of the aircraft in the LTO and CCD phases,

TABLE 3 The payoff matrix for three players.

Players				Small and medium-sized airlines	
				AR (z)	NO ($1 - z$)
Government	AR (x)	Major airlines	AO (y)	$(\Pi_{GO1}, \Pi_{MA1}, \Pi_{SA1})$	$(\Pi_{GO2}, \Pi_{MA2}, \Pi_{SA2})$
			NO ($1 - y$)	$(\Pi_{GO3}, \Pi_{MA3}, \Pi_{SA3})$	$(\Pi_{GO4}, \Pi_{MA4}, \Pi_{SA4})$
	NR ($1 - x$)	Major airlines	AO (y)	$(\Pi_{GO5}, \Pi_{MA5}, \Pi_{SA5})$	$(\Pi_{GO6}, \Pi_{MA6}, \Pi_{SA6})$
			NO ($1 - y$)	$(\Pi_{GO7}, \Pi_{MA7}, \Pi_{SA7})$	$(\Pi_{GO8}, \Pi_{MA8}, \Pi_{SA8})$

stabilization. Based on the obtained replicated dynamic equations, the Jacobian matrix was calculated as shown in Eq. 18. First, it is an ESS only if it is a pure strategy Nash equilibrium and a strict Nash equilibrium (Selten, 1988; Ritzberger and Weibull, 1995; Friedman, 1998), while E_9 , on the other hand, is a hybrid strategy equilibrium and therefore not be an ESS. Second, in this case, we can use the eigenvalue and the following criterion to determine if the equilibrium point is an ESS (Lyapunov, 1992): 1) When the real part of the three eigenvalues is negative, the equilibrium point is ESS; 2) When the real part of the three eigenvalues is positive, it is not ESS, i.e., the unstable point; 3) When the real part of one or two eigenvalues are positive, it is the saddle point.

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix}$$

$$= \begin{bmatrix} (1-2x)(a-cy-bz) & -cx(1-x) & -bx(1-x) \\ ey(1-y) & (1-2y)(ex+fz+d) & fy(1-y) \\ bz(1-z) & hz(1-z) & (1-2z)(bx+hy+g) \end{bmatrix} \quad (18)$$

Accordingly, by solving Eq. 18, Table 4, shows the eigenvalues of the Jacobian matrices associated with each equilibrium point. Based on the analysis of the sign of each eigenvalue, the four equilibria E_1 , E_3 , E_4 , and E_7 must not be ESSs for the following reasons.

- For an equilibrium point of E_1 , the sign of the eigenvalues of λ_1 must be positive because $a > 0$. This point is not the ESS.
- (2) For the three equilibrium points of E_3 , E_4 and E_7 , the sign of λ_1 is positive because $a - b > 0$, $a - c > 0$ and $a - b - c > 0$. These points are not the ESS.

Therefore, E_2 , E_5 , E_6 and E_8 have the potential to become the ESS. Suppose that:

$$\begin{aligned} \mu_1 &= b + g = CP_{SY} - C_{SY} - t_Y E_{SY} - [CP_{SN} - C_{SN} - t_N (E_{SN} - E_S) - t_Y E_S]; \\ \mu_2 &= d + e = CP_{MY} + P_{MO} - C_{MY} - (CP_{MN} - C_{MN} - P_{MI}); \\ \mu_3 &= b + g + h = CP_{SY} - C_{SY} - t_Y E_{SY} - [CP_{SN} - C_{SN} - t_N (E_{SN} - E_S) - t_Y E_S - P_{MS}]; \\ \mu_4 &= d + e + f = CP_{MN} + P_{MI} - C_{MY} - (CP_{MN} - C_{MN} - P_{MS} - P_{MO}) \end{aligned} \quad (19)$$

It can be seen that $\mu_3 > \mu_1$ and $\mu_4 > \mu_2$. By analyzing the positives and negatives of the expressions, the asymptotic stability conditions are shown in Table 4.

TABLE 4 Equilibrium point stability analysis.

Equilibrium points	Eigenvalue			Symbols of three eigenvalues	Asymptotic stability condition	Attributes
	λ_1	λ_2	λ_3			
$E_1 (0, 0, 0)$	a	d	g	+, N, N	/	unstable or saddle point
$E_2(1, 0, 0)$	$b + g$	$d + e$	$-a$	N, N, -	$\mu_1 < 0, \mu_2 < 0$	ESS
$E_3 (0, 1, 0)$	$a - c$	$g + h$	$-d$	+, N, N	/	unstable or saddle
$E_4 (0, 0, 1)$	$a - b$	$d + f$	$-g$	+, N, N	/	unstable or saddle
$E_5(1, 0, 1)$	$b - a$	$-b - g$	$d + e + f$	-, N, N	$\mu_1 > 0, \mu_4 < 0$	ESS
$E_6(1, 1, 0)$	$c - a$	$-d - e$	$b + g + h$	-, N, N	$\mu_2 > 0, \mu_3 < 0$	ESS
$E_7 (0, 1, 1)$	$-f - d$	$-h - g$	$a - b - c$	N, N, +	/	unstable or saddle
$E_8(1, 1, 1)$	$-f - e - d$	$-h - g - b$	$b - a + c$	N, N, -	$\mu_4 > 0, \mu_3 > 0$	ESS

Note: “-” indicates a negative eigenvalue; “+” indicates a positive eigenvalue; “N” indicates the eigenvalue’s attribute uncertainty. Bold values represent the 4 possible ESS.

TABLE 5 Strategy selection in game scenarios.

Strategy	Stakeholders			Equilibrium points
	Government	Major airlines	Small and medium-sized airlines	
Incubation	AR	NO	NO	$E_2 (1, 0, 0)$
Discovery	AR	NO	AO	$E_6 (1, 0, 1)$
Rapid development	AR	AO	NO	$E_5 (1, 1, 0)$
Steady development	AR	AO	AO	$E_8 (1, 1, 1)$

4.1.2 The game scenario of mixed emission reduction policies

In accordance with Section 5.1, the evolutionary game model is divided into the following four scenarios.

- (1) Incubation: Given the conditions shown in Table 4; Eq. 19, the small and medium-sized airline’s net payoff when it chooses the AO strategy (i.e., $CP_{SY} - C_{SY} - t_Y E_{SY}$) is lower than its net payoff when it chooses the NO strategy (i.e., $CP_{SN} - C_{SN} - t_N (E_{SN} - E_S) - t_Y E_S$). Moreover, the major airline’s net payoff when it chooses the AO strategy (i.e., $CP_{MY} + P_{MI} - C_{MY}$) is lower than its net payoff when it chooses the NO strategy (i.e., $CP_{MN} - C_{MN} - P_{MO}$). In this vein, the corresponding evolutionary strategy is (AR, NO, NO).
- (2) Discovery: Given the conditions shown in Table 4; Eq. 19, for the small and medium airlines, the benefit of adopting the AO strategy (i.e., $CP_{SY} - C_{SY} - t_Y E_{SY}$) is greater than its benefit of adopting the NO strategy (i.e., $CP_{SN} - C_{SN} - t_N (E_{SN} - E_S) - t_Y E_S$). Additionally, for the major airlines, the net payoff when adopting the AO strategy ($CP_{MY} + P_{MI} - C_{MY}$) is smaller than its net payoff when choosing the NO strategy (i.e., $CP_{MN} - C_{MN} - P_{MO} - PO_{SM}$). In this vein, the corresponding evolutionary strategy is (AR, NO, AO).
- (3) Rapid development: Given the conditions shown in Table 4; Eq. 19, for the major airlines the benefit of adopting the AO strategy (i.e., $CP_{MY} + P_{MI} - C_{MY}$) is greater than its benefit of adopting
- (4) Steady development: Given the conditions shown in Table 4; Eq. 19, for the small and medium-sized airlines, the net payoff of choosing the AO strategy (i.e., $CP_{SY} - C_{SY} - t_Y E_{SY}$) is greater than its net payoff when it chooses the NO strategy (i.e., $CP_{SN} - C_{SN} - t_N (E_{SN} - E_S) - t_Y E_S - PO_{MS}$). In this vein, the corresponding evolutionary strategy is (AR, AO, AO).

the NO strategy (i.e., $CP_{MN} - C_{MN} - P_{MO}$). However, for the small and medium-sized airlines, the net payoff of choosing the AO strategy (i.e., $CP_{SY} - C_{SY} - t_Y E_{SY}$) is lower than its net payoff when it chooses the NO strategy (i.e., $CP_{SN} - C_{SN} - t_N (E_{SN} - E_S) - t_Y E_S - PO_{MS}$). In this vein, the corresponding evolutionary strategy is (AR, AO, NO).

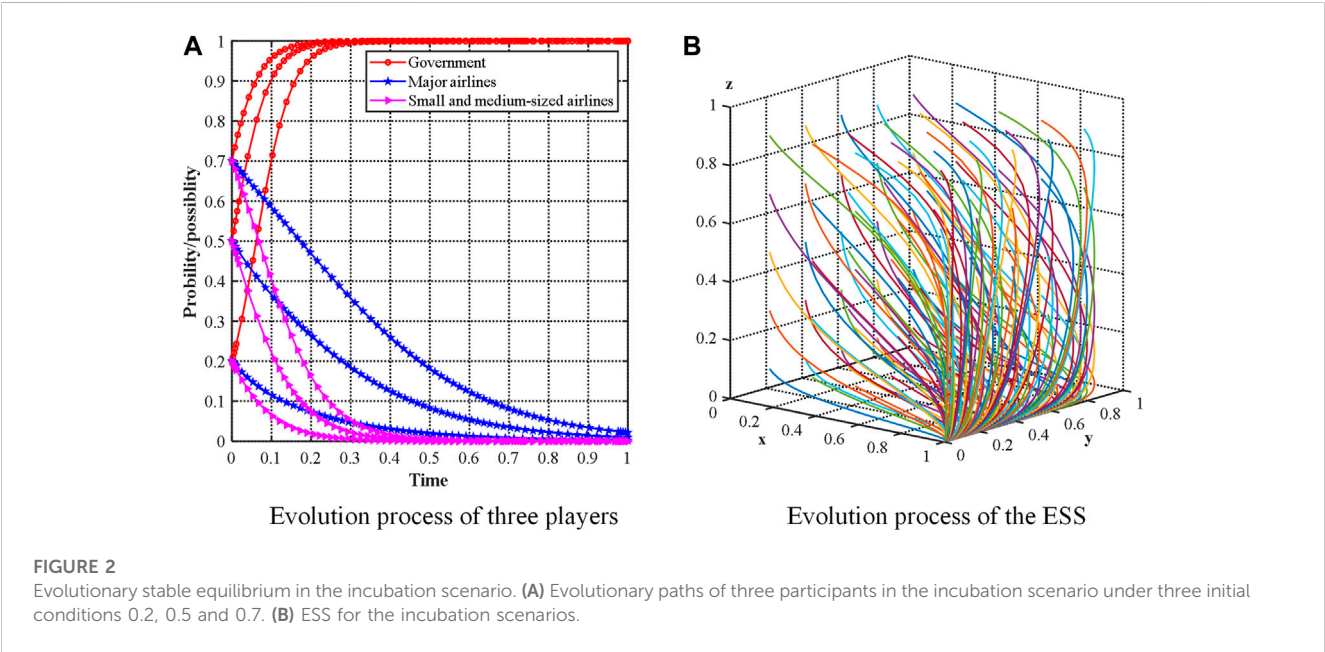
Table 5 shows four possible game scenario strategy choices.

5 Empirical analysis and simulation

According to the above analysis, in this section, the stability of the mixed carbon tax and carbon trading is influenced by many parameters. We use numerical simulations to further investigate the evolution of the three players’ decisions.

TABLE 6 Parameters for different scenarios.

Parameters	P_{MO}	P_{MI}	CP_{MN}	CP_{MY}	C_{MY}	C_{MN}	CP_{SN}	CP_{SY}	E_S	E_{SY}
Incubation	0	0	34	28	20	20	9	6	9	9
Discovery	3	3	36	30	25	20	5	11	7.8	6.6
Rapid development	13.5	22.5	36	41	40	20	9	6.8	8.9	8.4
Steady development	13.5	22.5	36	41	40	20	5	11	8.8	6.6
Parameters	E_{SN}	C_{SY}	C_{SN}	C_{S1}	C_{S2}	PO_{MS}	PO_{SM}	t_Y	t_N	θ
Incubation	9	6	6	12.4	0.7	0.9	3.4	3.8	6	0.1
Discovery	9	12	12	17.6	1.0	0.5	3.6	3.8	6	0.1
Rapid development	9	7.5	7.5	22.6	1.2	0.5	3.6	3.8	4	0.1
Steady development	9	12	12	24.7	1.3	8.5	3.6	3.8	6	0.1



5.1 Data collection and parameter settings

In this paper, we conducted numerical simulations using MATLAB 2020a software. Numerical simulations can visualize the iterations of the players' strategies, providing a quantitative analysis of the interactions. Thus, it is shown how their strategy evolves at each stage under different parameters. For the initial parameter setting of the model, we follow two principles: 1) refer to reality and 2) consider the logical relationship between the parameters. The following are the parameters for each scenario.

Airlines' size was determined as follows: first, a list was made of all airlines in order of their historical carbon emissions, from largest to smallest. The top airlines were then identified as major airlines until the total carbon emissions of all major airlines accounted for half of the total airline carbon emissions (Zhang et al., 2017). Air China (CA) and Shanghai Airlines (FM) represent the major airlines and small and medium-sized airlines as case

studies. Based on Air China and Shanghai Airlines' flight schedules, fleet information, and flight execution rates for the summer/fall and winter/spring seasons, a "bottom-up" approach was used to calculate the airlines' carbon emissions and fuel consumption for 2019. The calculated fuel consumption for CA and FM with the NO strategy (NO strategy using only TAF) is approximately 9 and 3 ($\times 10^6$ t), respectively. The ratios of SAF_{SY} to TAF_{SY} and SAF_{MY} to TAF_{MY} were both 6:4 when they adopted the AO strategy. Compared to TAF, SAF can reduce carbon emissions by up to 80% (Brueckner and Abreu, 2017). According to related studies, we set α and β as 3 (Hu R et al., 2020) and 1 (Moore et al., 2017; Heyne et al., 2021), respectively. In addition, P_{SAF} is approximately three times more expensive than P_{TAF} (Tanzil et al., 2021). Therefore, we can set P_{TAF} and P_{SAF} as 7 and 2, respectively.

Enterprises participating in carbon trading are required to pay entry fees, annual fees, etc., and the transaction fees for negotiated bargaining and pricing transfer transactions alone amount to 5% of

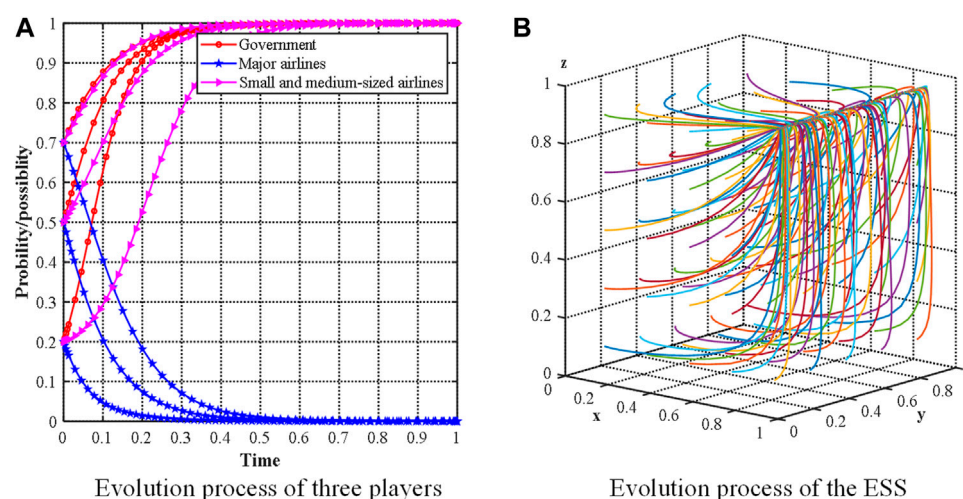


FIGURE 3

Evolutionary stable equilibrium in the discovery scenario. (A) Evolutionary paths of three participants in the discovery scenario under three initial conditions 0.2, 0.5 and 0.7. (B) ESS for the discovery scenarios.

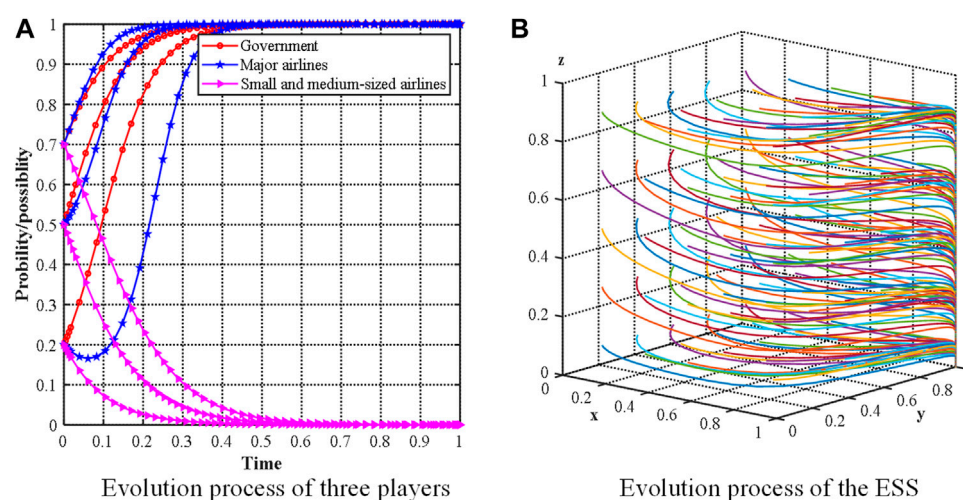


FIGURE 4

Evolutionary stable equilibrium in the rapid development scenario. (A) Evolutionary paths of three participants in the rapid development scenario under three initial conditions 0.2, 0.5 and 0.7. (B) ESS for the rapid development scenarios.

the transaction value. In addition, the government can obtain more implicit benefits from an active financial market. Therefore, θ is set to 0.1 (Fang et al., n. d.). The government tends to have lower inputs than firms using the AR strategy; thus, it can be assumed that the cost of the government using the AR strategy is lower than that of the major airlines and small and medium airlines using the AO strategy (Li et al., 2019). Therefore, we set parameter $C_{S1} = \frac{0.9(C_{MY} + C_{SY})}{2}$, $C_{S2} = \frac{0.1(C_{MN} + C_{SN})}{2}$. The impact of public opinion on companies' brand image can reach up to 23.89% of its profits (Li et al., 2018). In this paper, we set $PO_{SM} = 0.1CP_{MN}$ and $PO_{MS} = 0.1CP_{SN}$. Notably, Simulated systems evolve in virtual time t , not in real time.

In addition, some parameters were rounded to facilitate numerical simulation. Other parameter settings for different scenarios, based on actual conditions and recommendations from civil aviation practitioners, are shown in Table 6.

5.2 The dynamic evolutionary paths

Scenario analysis helps to explore the potential evolution of factors under different policy and economic scenarios on the differential impact of future carbon emission trends, and thus to quantify the path to achieve future carbon reduction targets. The

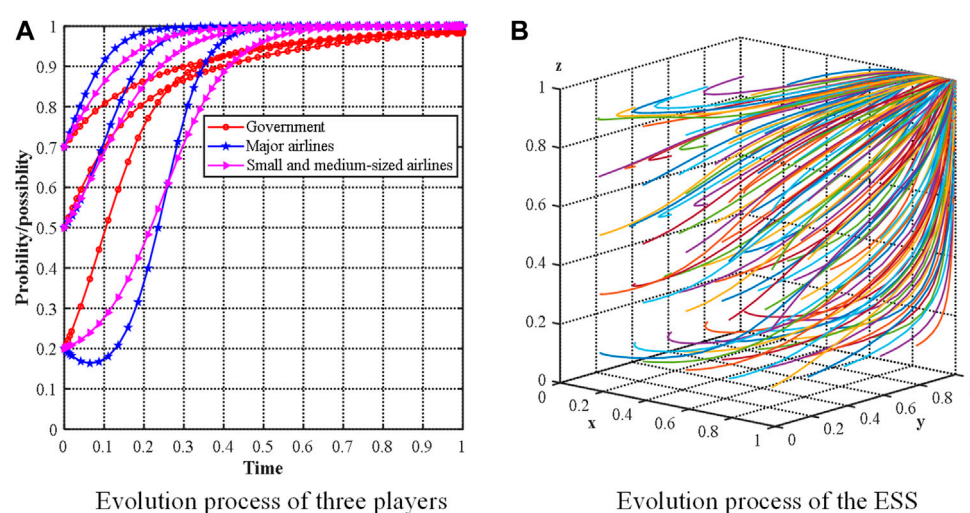


FIGURE 5

Evolutionary stable equilibrium in the steady development scenario. (A) Evolutionary paths of three participants in the steady development scenario under three initial conditions 0.2, 0.5 and 0.7. (B) ESS for the steady development scenarios.

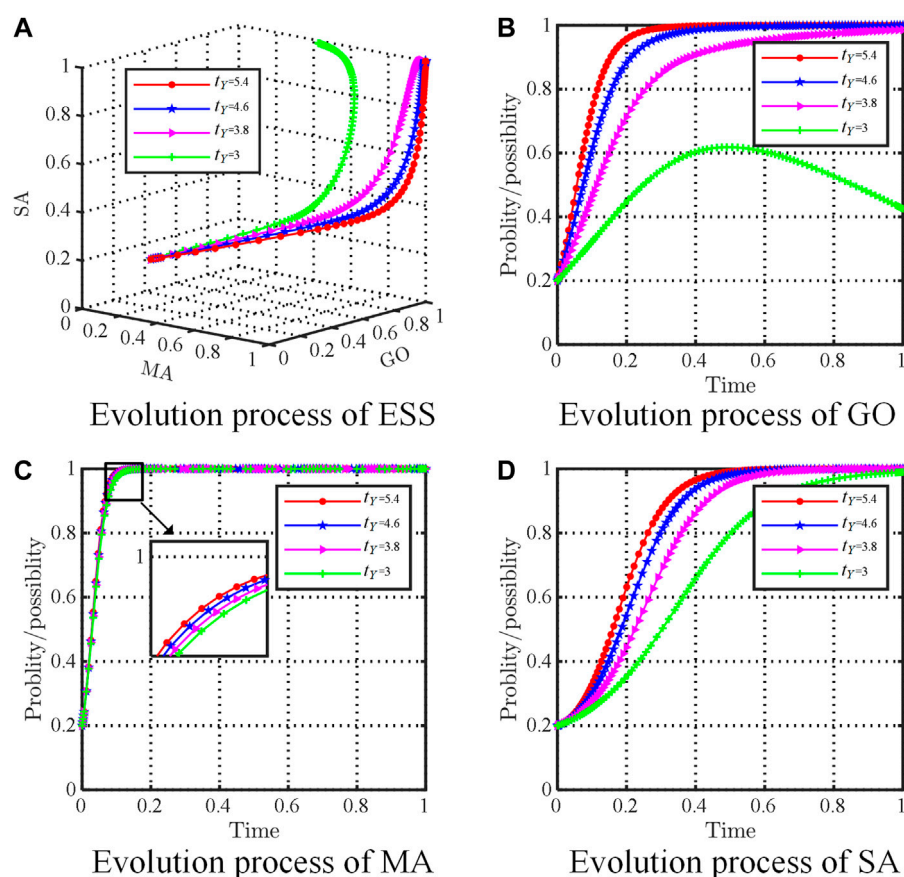


FIGURE 6

The impact of t_Y . (A) Evolution process of ESS. (B) Evolution of GO. (C) Evolution of MA. (D) Evolution of SA. (The GO denotes government, MA denotes major airlines, and SA denotes small and medium-sized airlines).

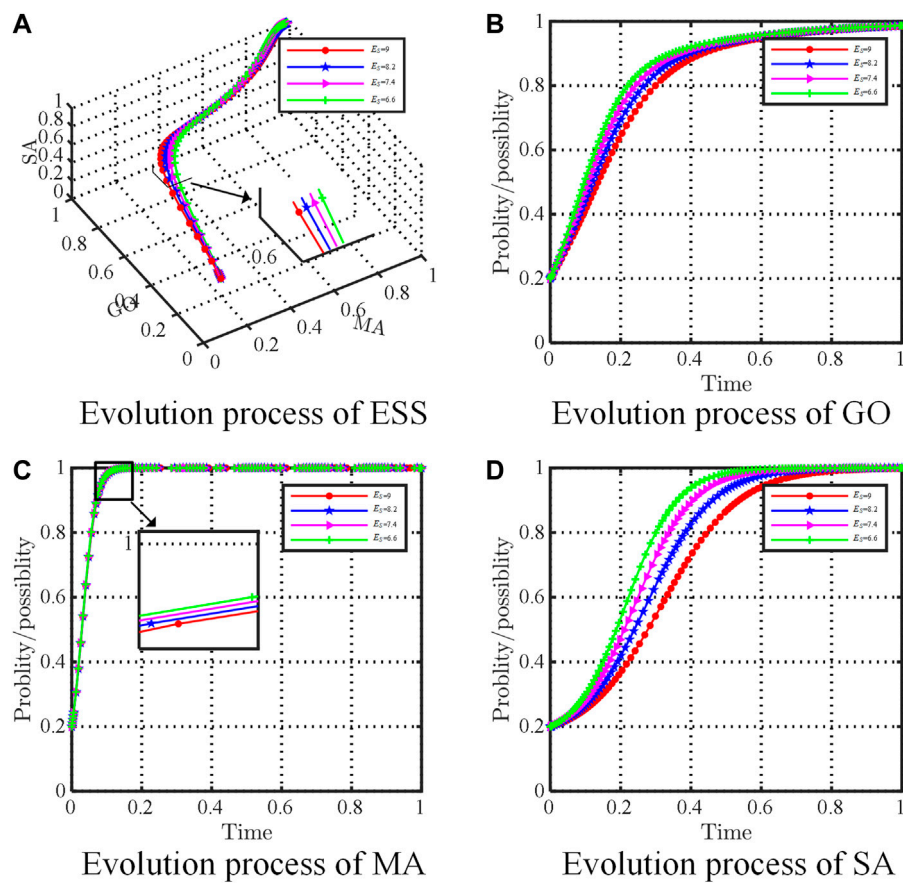


FIGURE 7

The impact of E_5 . (A) Evolution process of ESS. (B) Evolution of GO. (C) Evolution of MA. (D) Evolution of SA. (The GO denotes government, MA denotes major airlines, and SA denotes small and medium-sized airlines).

following are the numerical simulations of the four scenarios of the evolutionary game.

5.2.1 Dynamic evolutionary paths of incubation

Based on the stable conditions calculated above for the incubation scenario (i.e., $\mu_1 < 0$, $\mu_2 < 0$), the values corresponding to different parameters are simulated numerically. As shown in Figure 2A, with initial conditions of 0.2, 0.5 and 0.7, the possibility of the government adopting the AR strategy continuously increases, while the possibility of the major airlines and small and medium-sized airlines adopting the AO strategy continuously decreases. To verify that the equilibrium point E_2 (1, 0, 0) in the evolutionary model is stable, using MATLAB 2020b software, the three players' different initial strategies were simulated by looping through the generation of random x , y and z points. Figure 2B shows the decision-making trends in a tripartite evolutionary game with multiple colour lines, which eventually converge to E_2 (1, 0, 0). Specifically, in this scenario, the government decides to initiate and induce the major airlines and small and medium-sized airlines to implement a carbon reduction strategy (i.e., the AO strategy) through a hybrid mechanism consisting of a carbon tax and carbon trading. However, the government

allocates carbon allowances that are greater than or equal to the emissions of the major airlines using the NO strategy (Hu X et al., 2020), and the government sets a progressive tax threshold that is greater than the emissions of the small and medium-sized airlines using the NO strategy. Therefore, the government realizes that readjusting the carbon allowances and the progressive tax threshold is likely to achieve satisfactory results.

5.2.2 Dynamic evolutionary paths of discovery

Figure 3 shows the discovery scenario where each parameter corresponds to a stable condition involving $\mu_1 > 0$ and $\mu_4 < 0$. As shown in Figure 3A, with initial conditions of 0.2, 0.5 and 0.7, the possibility of the government adopting the AR strategy and the possibility of the small and medium-sized airlines choosing the AO strategy grow over time, while the possibility of the major airlines choosing the NO strategy continually decreases. MATLAB 2020b software generates random initial strategy points x , y and z to run numerical simulations. Figure 3B shows decision-making trends in a tripartite evolutionary game with multiple colour lines, which eventually converge to E_5 (1, 0, 1). Specifically, in this scenario, the government recognizes the deficiencies in the incubation scenario and lowers the threshold of the progressive taxation system, thus prompting small and medium-sized airlines to

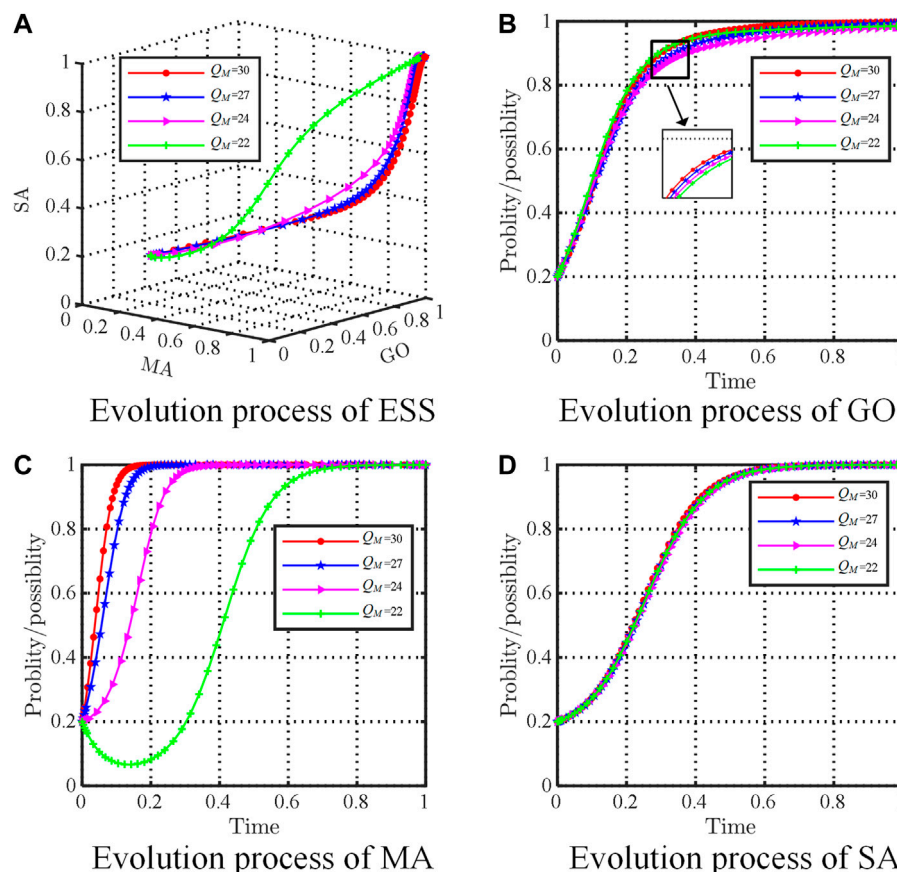


FIGURE 8

The impact of Q_M . (A) Evolution process of ESS. (B) Evolution of GO. (C) Evolution of MA. (D) Evolution of SA. (The GO denotes government, MA denotes major airlines, and SA denotes small and medium-sized airlines).

choose the AO strategy. Although the carbon allowances allocated to the major airlines is increased, the major airlines still chooses to implement the NO strategy since its payoff with the AO strategy is still greater than that with the NO strategy (the reason may be due to the increased costs of the major airlines with less subsidy when using SAF), which echoes the findings of Santos and Delina (Santos and Delina, 2021) that driving carbon reductions requires strong multistakeholder partnerships between airlines and government.

5.2.3 Dynamic evolutionary paths of rapid development

As shown in Figure 4A, with initial conditions of 0.2, 0.5 and 0.7, the possibility of adopting the AR and NO strategies for the government and major airlines, respectively, increases with time. The evolutionary probability of the small and medium airlines, on the other hand, has a different trend. We simulated the evolutionary model using MATLAB 2020b by generating random initial strategy points x , y , and z . The lines of different colors in Figure 4B together show the evolution of the unfixed initial strategies of the three players. After several evolutions, these lines converge to the equilibrium point E_6 (1, 1, 0). In this scenario, the government further reduces the carbon allowances allocated to the major airlines. To avoid purchasing additional carbon allowances, the major airlines uses a strategy that mixes SAF and TAF (i.e., the NO strategy) to reduce the carbon emissions it generates. However, the small

and medium-sized airlines learned that the revenue from adopting the AO strategy could not cover the expenses of adopting the NO strategy. Therefore, the small and medium-sized airlines prefers to implement the NO strategy.

5.2.4 Dynamic evolutionary path of steady development

Based on the stable conditions calculated above for the steady development scenarios (i.e., $\mu_4 > 0$, $\mu_3 > 0$), the values corresponding to different parameters are simulated numerically. As shown in Figure 5A, with initial conditions of 0.2, 0.5 and 0.7, both the major airlines and small and medium-sized airlines are willing to adopt the AO strategy when the government adopts the AR strategy. Moreover, AO strategies tend to evolve faster when players have a greater initial willingness to adopt them. To verify that the equilibrium point E_8 (1, 1, 1) in the evolutionary model is asymptotically stable, using MATLAB 2020b software, the three players' different initial strategies were simulated by looping through the generation of random x , y and z points. Figure 5B shows the decision-making trends in a tripartite evolutionary game with multiple colour lines, which eventually converge to E_2 (1, 1, 1). Specifically, in this scenario, the government realizes that reasonable coordination of carbon tax and carbon trading, building on their strengths and avoiding their weaknesses, will yield satisfactory results. Provided that the carbon tax

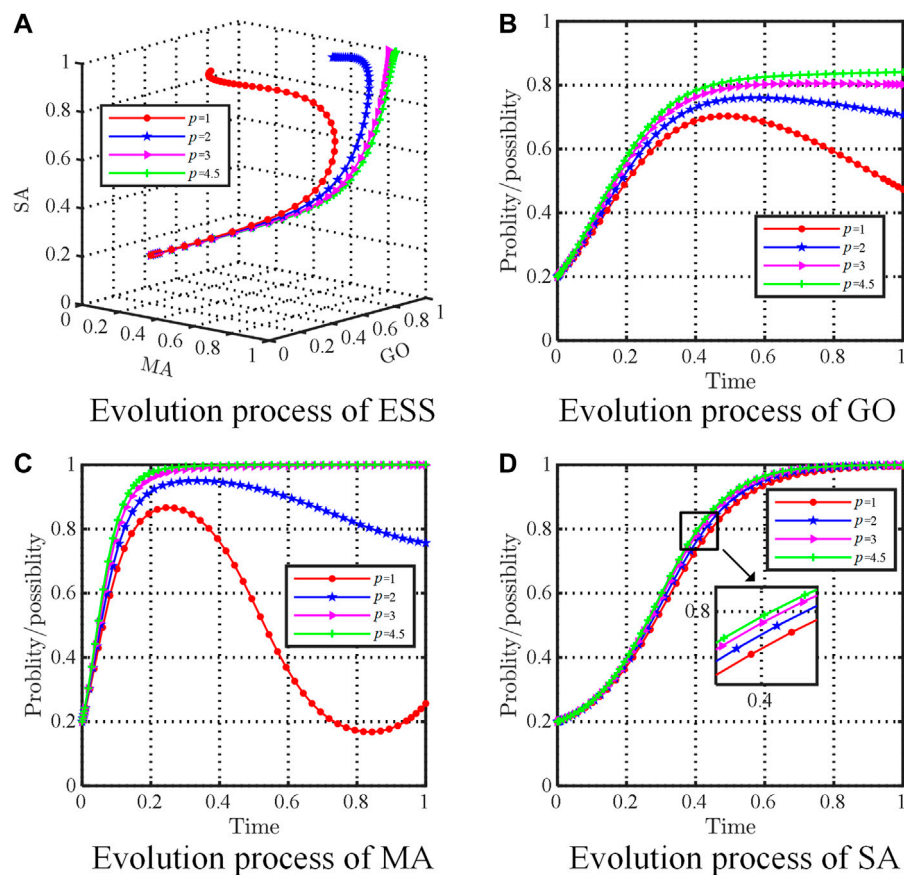


FIGURE 9

The impact of p . (A) Evolution process of ESS. (B) Evolution of GO. (C) Evolution of MA. (D) Evolution of SA. (The GO denotes government, MA denotes major airlines, and SA denotes small and medium-sized airlines).

and carbon trading without the AO strategy exceed the cost with the AO strategy (i.e., emission abatement cost, including P_{SAF}), the major airlines and small and medium-sized airlines certainly prefer the AO strategy.

5.3 Sensitivity analysis of key parameters

Sensitivity analysis determines which parameters have a significant impact on the system and thus obtains the sensitivity of the system to changes in the parameters.

5.3.1 The dynamic impact of the tax parameter t_Y

Assess the stability in the presence of regular carbon taxes, the parameter t_Y is set at 5.4, 4.6, 3.8, and 3. Figure 6A shows the evolutionary results. The MA and SA evolutionary paths tend to adopt the AO strategy when the regular carbon tax is relatively high, and both eventually reach a steady state. However, as the value of t_Y decreases, the GO tends to adopt the NR strategy, which provides some protection for itself to obtain economic benefits.

Figure 6B shows the effect of t_Y on the evolutionary path of the GO. When $t_Y = 5.4$, i.e., when the value of the punitive carbon tax is higher, the evolutionary time for the GO to reach asymptotic

stability is shorter. When $t_Y = 3.8$, the GO reaches asymptotic stability for longer than $t_N = 5.4$, which means that as the value of the regular carbon tax decreases, the evolution of the GO toward the AR strategy gradually slows. Put differently, the smaller the value of t_Y is, the more negative the GO is in regulating the airline's carbon emissions. When $t_N = 3$, the possibility of the GO adopting the AR strategy increases and then decreases, and it may even abandon the AR strategy. This is because when the GO attempts to reduce the regular carbon tax, the GO chooses the NR strategy to reduce the cost of regulation since the SA still chooses the OA strategy.

The evolutionary path of the MA's abatement strategy is shown in Figure 6C. When the t_Y value gradually decreases, the time for the MA to evolve into the AO strategy gradually increases, but the speed of evolution does not change significantly. This is because, in addition to GO factors, public opinion also influences enterprises' abatement behavior. For example, Zhang et al. found that public opinion drives firms' low-carbon behavior (Zhang et al., 2013). Therefore, at the time of a gradual increase in the SA's choice of the AO strategy, the MA relaxes its vigilance because public opinion is directed toward the SA while slightly increasing the evolutionary time for choosing the AO strategy.

Figure 6D illustrates the evolutionary process of the SA's dynamic strategy. As the t_Y value decreases, the time for the SA

to evolve into the AO strategy gradually increases. As the regular carbon tax decreases, the SA realizes that even if it does not reduce emissions, it will not incur excessive carbon tax costs and at the same time can avoid the high cost of SAF. Therefore, within a certain range, the higher the value of a regular carbon tax is, the greater the willingness of the SA to adopt the AO strategy.

5.3.2 The dynamic impact of the tax parameter E_S

When the threshold values of progressive taxation are taken as 9, 8.2, 7.4 and 6.6, the evolutionary path are shown in Figure 7A. When the threshold value is low, the GO tends to adopt the AR strategy and eventually tends to stabilize. As the E_S value decreases in the evolutionary game process, the possibility of the SA adopting the AO strategy increases and finally reaches asymptotic stabilization (Figure 7A). This result indicates that the threshold value of progressive taxation has some influence on the SA's strategy choice.

Figure 7C illustrate the evolutionary path of the MA's strategy. The reduction in the threshold has almost no effect on the MA; however, it has a significant effect on the GO and SA (Figures 3B,D).

Figure 7B illustrate the evolutionary path of the GO's strategy. As the threshold value of progressive taxation decreases, the GO has an increasing rate of evolution toward the AR strategy. The GO believes that a decrease in the E_S value leads to an increase in the possibility of the SA adopting the NO strategy. The GO increases its rate of evolution toward the AR strategy to prevent the SA from adopting the NO strategy. Conversely, the threshold value should not be set too high; otherwise, it may increase policy resistance (Zhang X et al., 2019).

Figure 7D illustrate the SA's strategy. When the threshold of progressive taxation is low, the SA converges more rapidly toward the AO strategy, but when the threshold of progressive tax is high, the SA converges more slowly toward the AO strategy. Therefore, the progressive tax has an obvious positive effect on the SA's carbon reduction, but it should not be set too high or too low (Oishi et al., 2012).

5.3.3 The dynamic impact of the allowance parameter Q_M

To determine the influence of the carbon allowances on the evolutionary path of the system and its stability, the parameter Q_M is set at 30, 27, 24, and 22. The evolutionary paths are shown in Figure 8A. Under the influence of different carbon allowance values, the MA and SA tend to choose the AO strategy, which eventually tends to stabilize. Similarly, the GO's strategy eventually tends toward the AR strategy. Clearly, carbon allowance values have a significant effect on the MA's stable strategies.

The evolutionary path of the GO's strategy is demonstrated in Figure 8B. A change in carbon allowances has almost no effect on the GO. This is because the environmental cost, *etc.*, from the MA not reducing emissions will have a considerable impact on the GO if it does not adopt the AR strategy. However, it has a significant effect on the MA (Figure 3C).

This is shown in Figure 8C, when $Q_M = 22$, i.e., when the value of the carbon quota allocated to the MA is low, and the MA takes longer to reach asymptotic stability and shows a tendency to choose the NO strategy at the beginning. However, due to aggressive GO regulation and high SAF costs, the MA must finally adopt the AO strategy to maximize its own benefits. As carbon allowances are

increased, the time required for the MA to reach asymptotic stability decreases. An increase in carbon allowances yields more surplus carbon allowances for airlines actively reducing emissions, which improves the emission reduction revenue of this group of airlines (Fang et al., 2022).

In addition, Figure 8C illustrate the evolutionary path of the SA's strategy. The evolutionary path of the SA is constantly inclined toward the AO strategy under the influence of the GO's regulation and public opinion. However, since the SA is a small or medium-sized and not covered by the emission trading system, a change in carbon allowances hardly affects it.

5.3.4 The dynamic impact of the trading price parameter p

We set $p = 1, 2, 3$, and 4.5, corresponding to the carbon trading price in the hybrid mechanisms system. The effect of p on the evolutionary paths of the three players is illustrated in Figure 9A. When the carbon trading price is relatively high, the evolutionary paths of the MA and SA tend toward the AO strategy, and both eventually reach stability. The GO tends toward the AR strategy and eventually reaches asymptotic stability.

Figure 9B illustrates the path of the GO's dynamic strategy. When $p = 4.5$ and $p = 3$, that is, when the carbon trading price shows a medium or high value, the GO chooses to move toward the AR strategy. When $p = 2, p = 1$, that is, when the carbon trading price is low, the probability of the GO choosing the AR strategy increases and then decreases, and it may even abandon the AR strategy in favor of the NR strategy. The GO is the policy implementer, and the strength of its policy implementation is reflected in the carbon trading price. The GO sets an appropriate carbon trading price to help airlines reduce emissions (Xu et al., 2016).

Figure 9C illustrates the path of the MA's dynamic strategy. When $p = 4.5$ and $p = 3$, the evolutionary path of the MA tends toward the AO strategy. When $p = 3$, the possibility of the MA choosing the AO strategy first increases and then decreases. When p further decreases to 1, the evolutionary path of the MA first tends toward the AO strategy and then tends toward the NO strategy, but finally, the MA does not choose the NO strategy. The lower carbon trading price reduces the MA's willingness to have low-carbon operations, thus avoiding the purchase of high-priced SAF that leads to airline profit loss. The MA does not ultimately choose the NO strategy. A plausible reason is that passengers would like to pay additional fees for a green image (Hagmann et al., 2015), which leads to higher profits.

Figure 9D illustrates the path of the SA's dynamic strategy. The effects of different levels of carbon trading prices on the SA's evolutionary results are not significant. The change in the SA's evolutionary path is mainly due to PO_{MS} (i.e., the public opinion pressure on the SA to adopt the NO strategy when the MA adopts the AO strategy).

6 Discussion and implications

6.1 Discussion

The implementation of hybrid mechanisms is a multiparty coordination process involving multiple players. Essential to

achieving carbon reductions in civil aviation is finding the right solutions to satisfy the benefits of each player. This means that the interests of many parties need to be reconciled in order to achieve carbon reduction targets. Moreover, airlines need to find the right way to minimize emissions in response to hybrid mechanisms to maximize profits.

However, to our knowledge, few studies have investigated the use of hybrid carbon reduction mechanisms in civil aviation. The government and airlines are explored in this paper using a tripartite evolutionary game under carbon tax and carbon trading constraints. In addition to discussing the conditions for airlines to adopt carbon reduction strategies under the hybrid mechanism constraint (including 4 scenarios, i.e., incubation, discovery, rapid development, and steady development), we also analyze the sensitivity of relevant parameters, for example, the regular carbon tax price, carbon allowances, carbon trading price and the threshold of progressive taxation. Based on the numerical simulation results, the government and airlines are only willing to adopt emission reduction strategies as long as their interests are maximized, which is consistent with previous studies. (Chen and Hu, 2018) (Dixit et al., 2022) (Zhang J.J et al., 2019) (Zhang and Zhang, 2022) (Zhao X et al., 2020). The difference is that we use different carbon reduction policies for different types of airlines.

The government should first have a better understanding of the cost and benefits of airline emissions reduction, which requires considerable research work such as obtaining statistics and conducting interviews. Then, based on the cost and benefit information obtained, it needs to determine which airlines should be included in the emission trading system and which airlines should only pay the carbon tax. Similar to Zhang and Zhang, (2022) in their study on air pollution reduction in steel enterprises, steel enterprises were divided into Large Iron manufacturers and small and medium-sized steel manufacturers. Similarly, Li and Gao, (2022) classified green technology innovation enterprises into two categories, A and B.

As analyzed in sections 5.2.1–5.2.4, hybrid policies serve as facilitators. In the incubation scenario, the hybrid policy is still in its infancy. In this case, the government should take a dominant position in the development of carbon reduction in civil aviation. From a carbon tax perspective, the setting of immature progressive taxation thresholds substantially hinders the small and medium-sized airlines' carbon reduction behavior. From a carbon trading policy perspective, carbon allowances are not devised in a reasonable manner due to a lack of experience. This led to the major airlines making maximum profits without having to reduce emissions. In the discovery scenario and rapid development scenario, the government adjusts the relevant parameters in the mixed emission reduction policy to make the small and medium-sized airlines and major airlines adopt the AO strategy. Eventually, in the steady development scenario, the small and medium-sized airlines and major airlines adopt the AO strategy simultaneously under the premise that the government adopts the AR strategy.

This study uses an evolutionary game approach to solve the stakeholder decision making problem in carbon reduction. Evolutionary games assume that the participating agents are finitely rational. With the help of replicated dynamic

equations, players constantly modify and improve their behavior during the evolutionary process and eventually make decisions. It has high efficiency in the study of policy decision making. Advanced optimization algorithms have been widely used to solve berth scheduling problem problems (Kavoosi et al., 2019a; Kavoosi et al., 2019b; Dulebenets, 2021), vehicle routing problems (Pasha et al., 2022; Rabbani et al., 2022) and other research. It greatly outperforms some well-known metaheuristic algorithms. Recently, some scholars have used optimization algorithms based on evolutionary game theory to solve the conflict and decision making problems among stakeholders (Wang et al., 2022). The advantage of advanced optimization algorithms over traditional evolutionary game models is that solutions can be designed for a real-world problem, leading to better results. For example, Xu et al. Designed a game-based fuzzy logic control genetic algorithm to study the carbon emission reduction problem under the carbon tax mechanism (Xu et al., 2018). In the future, advanced optimization algorithms can be designed for the carbon emission reduction problem of civil aviation under a hybrid mechanism.

Implications
The policy and management recommendations are presented to facilitate the effective implementation of carbon reduction in civil aviation based on the findings of the study.

- (1) Rationalize the carbon tax and carbon trading and construct a coordinated hybrid mechanism. Due to institutional design and other reasons, the application of the two carbon reduction mechanisms may bring about overlap in the scope of regulation and coordination problems in terms of the cost or burden of emission reduction. Accordingly, it is necessary to coordinate through reasonable policy design to avoid policy contradictions and conflicts and to synergize the regulatory role of hybrid mechanisms in carbon emission reduction.
- (2) Coordinate different regulatory tools in terms of airline cost burden. Due to the uncertainty of the market price of carbon, there may be a large gap between this and the relatively transparent level of the carbon tax, which may lead to an inequitable burden between airlines subject to different mechanisms. To build a relatively fair environment for carbon abatement cost mechanisms, it is necessary to start with the design of the carbon trading and carbon tax mechanisms to achieve general consistency in terms of regulatory strength.
- (3) In addition, the government must subsidize airlines that adopt the AO strategy when implementing the hybrid mechanism. In the study, it was found that part of the reason for airlines not to adopt the AO strategy could be the high price of SAF. Therefore, airlines that use SAF fuel should be subsidized to varying degrees depending on the amount of fuel used.

7 Conclusion

An evolutionary game model involving the government, major airlines, and small and medium-sized airlines is established in this study to address the carbon emission abatement problem in civil aviation. As a result, the following conclusions can be drawn.

- (1) Although there are eight equilibrium points, only 4 have the potential to become the ESS. Depending on the conditions corresponding to the equilibrium point, four different scenarios can be classified. Each scenario represents a different stage of the government's implementation policy: the incubation scenario shows the immature stage of the government in implementing the hybrid mechanism; the discovery and rapid development scenarios can be regarded as the groping stage of the government in implementing the hybrid mechanism; and the steady development scenario shows that the stable state of (1, 1, 1) can be achieved with the gradual and substantial improvement of relevant laws and provisions. If the carbon trading, which binds the major airlines, and the carbon tax, which binds the small and medium-sized airlines, are developed and mature and the carbon emissions of airlines are reasonably regulated, then the hybrid mechanism is efficient and feasible and the ideal way to address the carbon emission abatement problem in civil aviation in the long run.
- (2) Several factors significantly influence the evolutionary trends of dynamic systems involving the three players. Carbon allowances and carbon trading prices have the most significant impact on the major airlines' strategic choices. The government sets an appropriate carbon allowance and carbon trading prices to constrain the major airline's carbon emission activities and further guide its behavioral strategies. The major airlines do not need to implement an AO strategy when the value of carbon allowances is too high; when it is too low, it will lead to increased pressure on the major airlines to reduce emissions. Similarly, the major airlines' strategy choice is more sensitive to fluctuations in carbon trading prices.
- (3) The small and medium-sized airlines' strategic choice is significantly influenced by the carbon tax and threshold. The government sets an appropriate regular carbon tax and thresholds to constrain small and medium-sized airlines' carbon emission activities and guide its behavioral strategies. Otherwise, insufficient or excessively high levels of the regular carbon tax and thresholds set by the government will be detrimental to the small and medium-sized airlines' choice of the AO strategy. In addition, public opinion plays a role in promoting the adoption of the AO strategy by airlines.

Compared to a single mechanism, a hybrid mechanism can ensure the achievement of civil aviation emission reduction.

There are some limitations of this paper: 1) This study focused on mixed SAF fuel as the primary means for airlines to implement emission reduction strategies. Future research could combine methods such as optimizing fleet structure and aircraft green technology application, thus enhancing the emission reduction effect. 2) By considering more carbon emission management policies, such as SAF subsidies, government incentives and penalties, this study would have

greater applicability. 3) To increase the feasibility of the model, the potential effect of uncertainty in some parameters is ignored. By considering more practical factors, more realistic conclusions can be drawn.

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

PZ: conceptualization, data curation, formal analysis, project administration, software, writing–original draft, and writing–review and editing. RD: data curation, formal analysis, methodology, supervision, validation, writing–original draft, and writing–review and editing. YW: funding acquisition, supervision, and writing–review and editing. QZ: Formal analysis, Validation, Writing–Review and Editing. LZ: Software, 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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Corporate social responsibility (CSR) in the service industry: a systematic review

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The objective of the current study is to perform a systematic review to the published articles upon the advancement of corporate social responsibility (CSR) in the service sector. This article analyzes the bibliometric information of the CSR-related articles linked to the service sector. The existing literature on CSR in the service industry were derived from the online WOS indexing dataset. Through completing a systematic review on existing academic articles, the current paper identifies the nations, universities/institutions, prolific researchers, high-profile journal that contributed to the advancement of CSR theory and practical applications. Moreover, the analytical graphs and bibliometric coupling shown the keyword co-occurrence to depict the academic relationship on the CSR advancement in the service industry. The systematic review adds to an in-depth knowledge of the progression behind CSR in the corporate environment and extends the CSR nexus researches.

KEYWORDS

systematic review, corporate social responsibility, service industry, keywords co-occurrence, meta analysis

Introduction

Corporate social responsibility, (CSR) has emerged as a vibrant subject of theoretical progression and academic scholarship, and its rigorous humanity-based basis has thus garnered the attention of both academics and professionals (Abbas et al., 2018; Moyeen et al., 2019; Chen & Lin, 2020). CSR scholars have tried to find the outcomes of CSR participation in terms of increasing service quality in the service industries over the previous few decades (Casado-Díaz et al., 2014; Andrew & Baker, 2020; Antonetti et al., 2021). In recent decades, the inquiry on corporate social responsibility (CSR) has grown exponentially. The existing studies aimed to address particular concerns relating to CSR, such as the financial performance (Atmeh et al., 2020; Okafor et al., 2021), the banking system (Ahmad et al., 2022), environmental issues, enterprise development, and its positive/negative consequences (Fukuda & Ouchida, 2020).

Due to the many characteristics of the service industry, CSR practices differ tremendously (Batool et al., 2016). Even though the examination of the production, fiscal employment, the economy and the strategies of CSR receives significant interest (Sadik-Zada et al., 2021), the analysis of the impact on the service sector obtains somewhat less. There is no universal agreement among businesses over the definition of sustainable development through the application of CSR concept (Freeman & Hasnaoui, 2011). As a result, there are still a significant number of research gaps in the investigation

about the connection between CSR and the service industry (Moyeen et al., 2019; Wut et al., 2022). Therefore, it is essential to perform a panoramic investigation on the relationship between corporate social responsibility and its effect on the qualitative improvement of the service business (Perrini et al., 2006; Husted & Allen, 2007; Rodrigues & Mendes, 2018; Gallardo-Vázquez et al., 2019). Throughout this paper, we want to provide contributions to the intellectual framework of CSR, one of the most important types of methods that would help facilitate environmental sustainability and managerial advancement, via a systematic review of the existing intellectual literature indexed in Web of Science (WOS) over the past decades.

This research explores the existing literature about impact CSR on the service industry and intends to be deepening researching the mechanism of how CSR researches progressed over the past 3 decades. The research objectives are as follows: 1) To make a systematic review to the relevant research on CSR to remark on the dearth of prior researches in related topics and give appropriate theoretical basis to the advancement of the service sector. 2) To identify the current progress of the CSR concept in the service industry from the perspectives of economic obligations, legal responsibilities, ethical responsibilities, and philanthropic responsibilities. 3) To identify and visualize the publishing years, prolific regions/nations, dedicated journals, supporting universities/institutions, the authors, as well as the CSR keywords in the service sector and the co-occurrence analysis. And 4) To examine the nuances of CSR concept in the future research agenda while presenting the overall systematic review during the implementation process of the current study. Through examining the WOS database, this systematic review intends to contribute to a consideration of the important effects of the service industry, the central influence of principle of corporate social responsibility.

In accordance with this line of thought, the structure of this study is set as follows: First, the next phase of the current research focuses on the research methodology elaboration. Next, to examine the impact that corporate social responsibility has on contemporary academic research via a systematic literature review to the relevant published articles. The current study identifies the countries, universities/institutions, prolific researchers, and high-profile journals that have contributed to the development of CSR theory and practical applications by completing a systematic review on existing academic articles. Furthermore, a thematic review was carried out in order to determine the keyword co-occurrence and keywords frequency for identifying the advancement of CSR theory and practical applications. The conclusion section includes a summary, a further elaboration on theoretical and practical contributions, as well as its exiting limitations.

Research methodology: a systematic review approach

In accordance with the Meta-Analysis methodology described by Liberati et al., in 2009 (Liberati et al., 2009), a complete evaluation of the literature is then performed. The

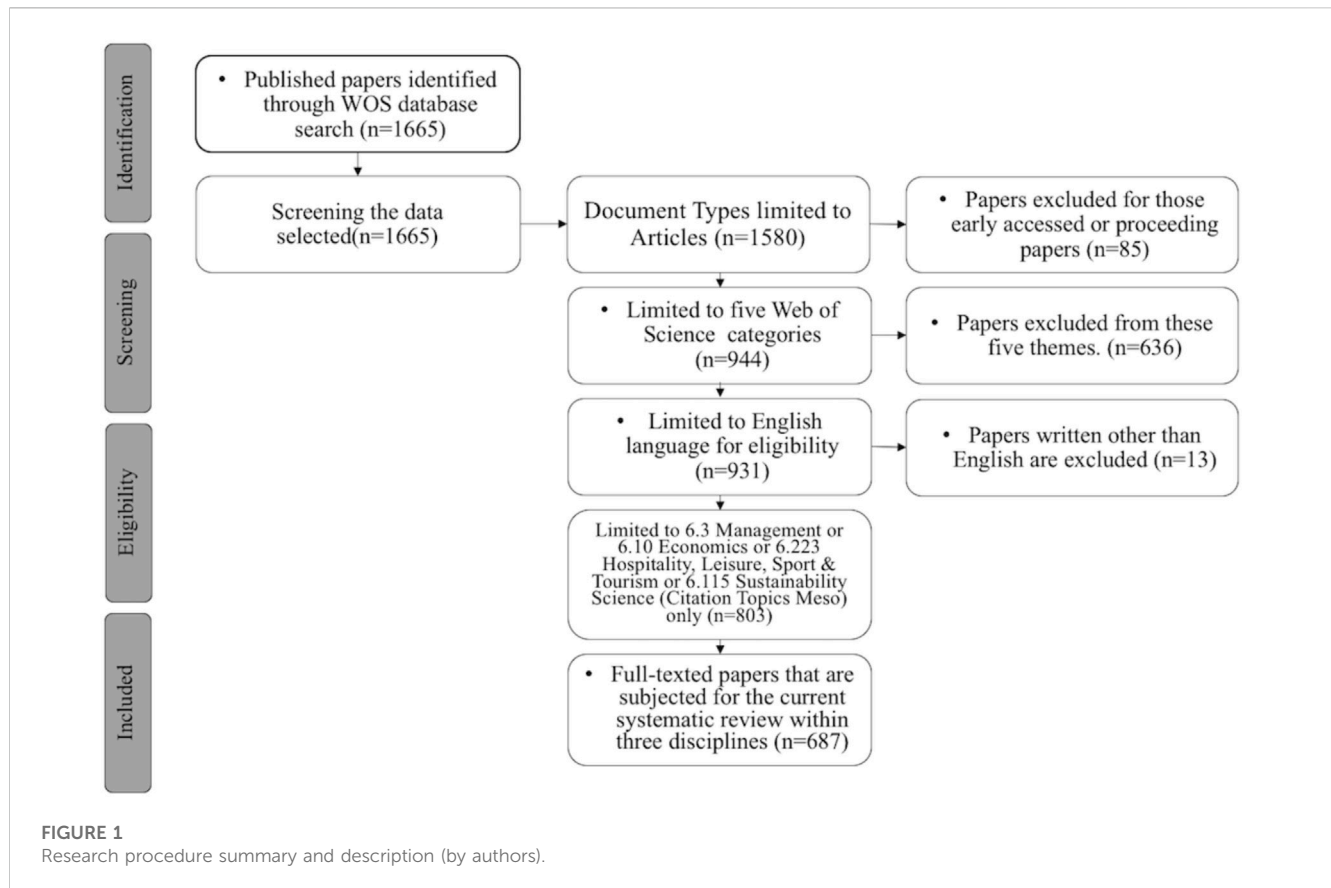
TABLE 1 The published years of papers related to CSR and service industry (Summarized by the authors).

Publishing year	Volume of publications
2023	7
2022	64
2021	109
2020	104
2019	78
2018	56
2017	65
2016	58
2015	56
2014	41
...	...
2002	1

authors carried out a comprehensive investigation for research articles conducted by scholars from around the world as well as blind-peer-reviewed papers in social sciences, business, decision sciences, economic management and accounting, as well as psychology disciplines (Oduro et al., 2021; Arici & Uysal, 2022). Adopting a database created from Web of Science for a concise systematic review effort (Baig et al., 2019), this study evaluated the dependability research articles with empirical data collected. In line with Liberati et al. (2009) and Adeyinka-Ojo et al., 2021 and Galeazzi et al., 2008, the current study discusses and expounds upon PRISMA statement checklists (Moher et al., 2011; Page et al., 2021), which are extensively utilized to conduct systematic review methodology in the field of social sciences and decision sciences.

To document the analytical procedure and inclusion criteria for the major databases, trustworthy research methods were developed prior to actual resources search. The authors conducted their research using WOS data since it provides the most accurate depiction of relevant articles. The academic world considers that WOS covers the most significant international publications. Thus, the authors are obligated to analyze this dataset using the WOS dataset. WOS was employed to discover publications approved for production in five disciplines that were included in the WOS indexing journals with titles/abstracts/keywords including the keywords selected for the current research. The published papers in different five disciplines are then exemplified in Table 1 for emphasizing the topic domains of major publications. The spectrum of publishing date is without restriction, since the current study was done in early 2023. The extracted and downloaded articles only extended to English-written papers.

A MS spreadsheets file was created to record the issued research paper data of the associated periodicals. The authors then completed the assessment of the papers that were chosen beforehand, which is also called screening in the PRISMA checklist (Moher et al., 2011;



Nawijn et al., 2019). The remaining publications complete texts were revisited and downloaded in accordance with the paper selection criteria (Zabavnik & Verbič, 2021). The selected papers were then incorporated in accordance with a transparent, reproducible, and a prior presumption-free methods (Popay et al., 2006; Pickering & Byrne, 2014; Alsamil et al., 2020). The bibliographic data in such chosen publications and the PRISMA checklist were input into Microsoft Excel spreadsheets for further data-analysis procedure (see Figure 1 below). Finally, 687 selected papers were subjected to a data collection procedure in order to improve the collected components and subsequent categorization. Then, these selected papers were examined attentively to extract and categorize in accordance with the current study.

Only for purposes of the current research, the authors input the following keywords into the WOS system to explore the title/abstracts/keywords of the published papers, yielding 1,665 results. In the meantime, the search criteria for the WOS database are shown as follows:

corporate social responsibility (Topic) and service (All Fields) and Article (Document Types) and Business or Management or Economics or Sociology or Hospitality Leisure Sport Tourism (Web of Science Categories) and English (Languages) and 6.3 Management or 6.10 Economics or 6.223 Hospitality, Leisure, Sport & Tourism or 6.115 Sustainability Science (Citation Topics Meso)

The titles of the choose articles reflect their production status. Even though database search resulted in the retrieval of 1,665 records, 85 papers were disqualified to be reviewed in

the current research because they are conference proceedings, review articles, other than peer-viewed articles. Those retrieved papers were reviewed further within the scope of the five fields, namely, Business or Management or Economics or Sociology or Hospitality Leisure Sport Tourism (Web of Science Categories). In the meantime, some of these irrelevant studies were omitted from further examination in the present research, and 944 papers remained, excluding 636 published papers. Furthermore, there were 13 papers excluded since they were not English-medium peer-viewed papers. Following this, the authors selected another four criteria under the Citation Topics Meso section, namely, 6.3 Management or 6.10 Economics or 6.223 Hospitality, Leisure, Sport & Tourism or 6.115 Sustainability Science, which led to a number of 803 papers remaining. Some of these entries were removed because they did not meet the eligibility standards and the entire text could not be extracted. As a result, the search result indicates that 687 articles have been published with the topic of the current study in the WOS system, which are closely connected to the five research areas that are the subject of the present study. Then, the current systematic review included empirical full-texted papers in total. The research procedure following the PRISMA checklist for assessing precedential research is then shown in Figure 1 above. The following analysis are further done through the facilitations of VOSviewer (a software application for establishing and displaying bibliometric connectivity structures) and Zotero (an open-sourced application for managing bibliographic information and pertaining to the research resources).

Research findings

The published years of CSR and service industry-related articles

Since the turn of the 20th century, expectations of businesses in the service sector have expanded, and the notion of corporate social responsibility (see Table 1 below), frequently abbreviated as CSR, has evolved throughout time to address these growing demands (Esen, 2013; Moyeen et al., 2019). Society's organizational structure has had a role in the evolution of the notion of corporate social responsibility (Dahlsrud, 2008). Previous study has compiled a compendium of the CSR literature in regard to the growth of the service sector in accordance with the concept of corporate social responsibility (e.g., Coles et al., 2014; Aragon-Correa et al., 2015; Farrington et al., 2017). The study of CSR ethics in the discipline of decision science may be used for a variety of purposes, including increasing commercial profitability, improving political performance, or improving stakeholder responsibility (Esen, 2013; Shin et al., 2021). There has been a significant amount of focus placed on corporate social responsibility (CSR) as a mechanism for enhancing the legitimacy of firms and the financial returns they generate (Carroll & Shabana, 2010; Wang & Sarkis, 2017; Xu et al., 2019). According to the findings of the precedential study, CSR has the potential to not only enhance the image and reputation of a service business but also to raise the motivation of its workforce. In addition, a greater awareness of the environment encourages businesses to accept responsibility for the consequences of their operations and to make a contribution toward environmentally responsible growth (Sadik-Zada, 2021). Therefore, corporate social responsibility is of utmost importance for the service businesses.

According to the findings of the previous studies, CSR has the potential to not only enhance the image and reputation of a service business (Sheldon & Park, 2011; González-Torres et al., 2021), but also to raise the motivation of its workforce (Aminudin, 2013; Zhang et al., 2021). The very first piece of inquiry examined the amount of papers on corporate social responsibility and the effect that it has on the service industry. Over the last several decades, there has emerged a significant focus in gaining a deeper comprehension of the occurrences of papers presented in Table 1. Despite the fact the very first piece of CSR issues was not publicly released until 2002, from 2015 there have been more than 50 pieces of content released per year. In the year 2020, there were over 104 articles published on the subject of the impact of CSR on the service sector. This conclusion demonstrates that the issue is novel and justifies the increasing emphasis that management/decision science scholars have been paying to it. In addition, the rise in ecological consciousness necessitates that businesses accept responsibility for the consequences of the activities and make contributions to the advancement of sustainable practices (Luo et al., 2020). In a similar vein, the enterprises' long-term commitment to charitable giving necessitates the deployment of CSR (Shin et al., 2021).

CSR academic researches in the top prolific and productive regions/nations

Multiple nations make substantial contributions to the topic of CSR researches in the service industry. The following dimension is based upon these top prolific nations among the years 2001 and 2023. The findings of these highest volume of publication in these twelve nations releasing CSR research are shown in Table 2 below. The position is determined by the quantity of periodicals.

The United States is the one of the most prolific nations, with 192 papers, demonstrating that United States scholars devote the widespread media coverage to CSR research among all academia. China is in second place with 128 articles, followed by the United Kingdom with 89 articles. In the meanwhile, Spain, Australia, South Korea, France, Germany, Canada, Netherlands, India and Italy are gaining a substantial place in CSR studies in the service sector and are leading the world ranking list, among others.

A bibliometric coupling is being developed in order to improve our understanding of connectivity across the nations that publish CSR topics. The process of bibliographic coupling takes place when two different papers extensively cite another publication. Regarding nations, it takes place when a manuscript from two different nations, each located in a different country, refers another paper within their respective articles. This demonstrates how the authors from different regions utilize linked material in their published papers. The results of the bibliometric connection are shown in Figure 2. Every sphere is a representation of a nation, and therefore the diameter reflects the amount contributed by that country. The bigger the size of the circle, greater significant of their academic contributions. According to Table 2, which can be seen above, the United States of America ranks as the country that published highest number of articles in the whole globe. In addition, the United States of America has the greatest bibliometric linkages to other nations, followed by China, the United Kingdom, South Korea, Australia and Spain.

The statistics of the most productive journals centering in the issue of CSR in the service industry

A further essential component of the quantitative evaluation is identifying the most prolific efforts among the journals that publishing CSR issues in the service sector. The top 12 academic publications are presented hereunder, as seen in Table 3 below. Statistics indicate that Journal of Business Ethics is the most productive journal, having produced 105 publications during the course of its existence. The Social Responsibility Journal and Journal of Business Research are ranking the second and the third place. Furthermore, International Journal of Hospitality Management, International Journal of Bank Marketing, Service Industry Journal, Journal of Services Marketing, Journal of Retailing and Consumer Services, Business Strategy and the Environment, International Journal of Contemporary Hospitality Management, Sustainability Accounting Management and Policy Journal and Service Business are some of the journals that have published over ten articles on CSR issues in the service industry.

CSR researches among the top publications made by different universities/institutions

One further essential component of the quantitative study is to identify the journals that produces the most scientific understanding about CSR in the service industry. According to the findings shown in Table 4, the Pennsylvania Commonwealth System of Higher Education (PCSHE) emerged as the most frequently cited institution, with 19 mentions, followed closely by Pennsylvania State University with 18 mentions. The State University System of Florida and Pennsylvania State University University Park also garnered significant attention with 17 and 15 mentions, respectively. Universidad de Cantabria, Universitat Ramon Llull, and the University System of Ohio exhibited notable presence with counts ranging from 12 to 14. Additionally, institutions such as Escuela Superior de Administracion y Direccion de Empresas

TABLE 2 The most prolific nations with academic attention to the CSR issues in the service industry.

Number	Name of the nations of the authors	Number of publications
1	The United States of America	192
2	China	128
3	The United Kingdom	89
4	Spain	84
5	Australia	67
6	South Korea	66
7	France	34
7	Germany	34
9	Canada	31
10	Netherlands	28
11	India	24
12	Italy	24

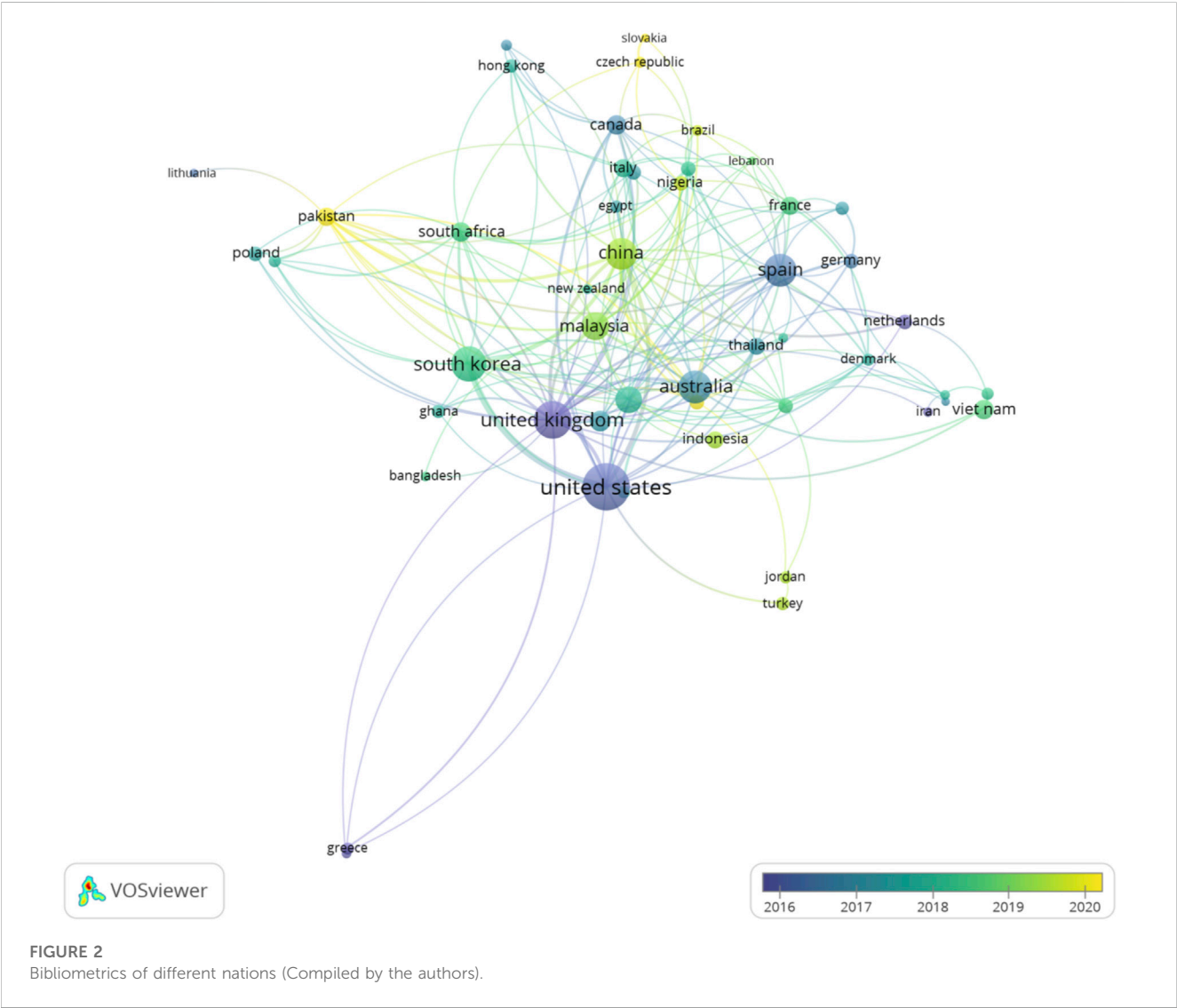


TABLE 3 Statistics of the most prolific journals (Summarized by the authors).

Number	Journal name	Number of publications
1	Journal of Business Ethics	105
2	Corporate Social Responsibility and Environmental Management	37
3	Journal of Business Research	34
4	International Journal of Hospitality Management	31
5	International Journal of Bank Marketing	22
6	Service Industry Journal	22
7	Journal of Services Marketing	20
7	Journal of Retailing and Consumer Services	19
9	Business Strategy and the Environment	18
10	International Journal of Contemporary Hospitality Management	17
11	Sustainability Accounting Managemen ^{et} 6 and Policy Journal	14
12	Service Business	12

TABLE 4 The most productive universities/institutions (Summarized by the authors).

Number	University/Institution name	Number of publications
1	Pennsylvania Commonwealth System of Higher Education PCSHE	19
2	Pennsylvania State University	18
3	State University System of Florida	17
4	Pennsylvania State University Park	15
5	Universidad de Cantabria	14
6	Universitat Romon Llull	12
7	University System of Ohio	12
7	Escuela Superior de Administracion y Direccion de Empresas Esade	10
9	Universitat de València	10
10	Bucharest University of Economic Studies	9
11	California State University System	9
12	Inha University/Nanyang Technological University	8

(ESADE), Universitat de Valencia, Bucharest University of Economic Studies, California State University System, and Inha University/Nanyang Technological University were mentioned with frequencies ranging from 8 to 10. These findings provide insights into the scholarly discourse and research landscape, showcasing the institutions that have attracted substantial academic attention within the scope of the systematic review.

The authors that produced the highest number of articles about CSR in the service sector in the WOS index system

Refer to [Table 5](#) to review the statistics regarding on these authors who published the most regularly on CSR literature

pertaining to the service industry. It has been discovered that Pérez, A. has produced or co-authored an aggregate of eleven papers. Mattila, A.S. has authored nine papers, while Ignacio, R. has written ten articles. In addition, Yuen, K. F., Su, L. J., Hur, W. M., Wong, Y. D., Peloza, J., Ana, Z. G., Garcia-Benau, M. A., Lee, S., Thai, V. V. each have published more than four publications to their names.

CSR academic researches keywords in the service sector and the co-occurrence analysis

The following part provides a more in-depth examination to the material in categories of research themes, which is a beneficial method for summarizing the characteristics of publications from

TABLE 5 The authors that produced the highest number of articles about CSR in the service sector (Summarized by the authors).

Number	Authors names	Papers
1	Pérez, A.	11
2	Ignacio, R	10
3	Mattila, A.S.	9
4	Yuen, K. F.	8
5	Su, L. J.	7
6	Hur, W. M.	7
7	Wong, Y. D.	6
7	Peloza, J.	4
9	Ana, Z. G.	4
10	Garcia-Benau, M. A.	4
11	Lee, S.	4
12	Thai, V. V.	4

the field of the CSR researches in the service industry, particularly in the tourism and hospitality sector. It is considered that the text elements of publications serve as the foundation for those key phrases analyzed in the current paper. In this investigation, keywords analytics are used to identify subject-related patterns throughout the chronology generated by the VOSviewer, a reference management application.

Consumers' choices to buy are heavily influenced by a variety of factors. Product quality (Kang & Hustvedt, 2014), the market price (Tsai et al., 2012), and corporate responsibility (Merz et al., 2018; Ahn et al., 2019) may be differentiated from one another when seen from the perspective of the enterprise's internal variables. When seen from the outside, they represent the reputation of the company (Hardeck & Hertl, 2014) and the image of the corporation (Srivastava & Wagh, 2020). In a highly competitive market environment where the number and quality of goods continue to increase, business operators are paying more attention to external issues. Thematic analysis is a research technique that scholars now use, and it may be used to find previously unknown topics and areas in the existing literature. It should come as no surprise that it is challenging to speculate on the kinds of subjects that will be of increasing interest in the years to come. The co-occurrences of the thematic keywords, on the other hand, encourages us to believe that the ongoing development pattern will not change in the near future.

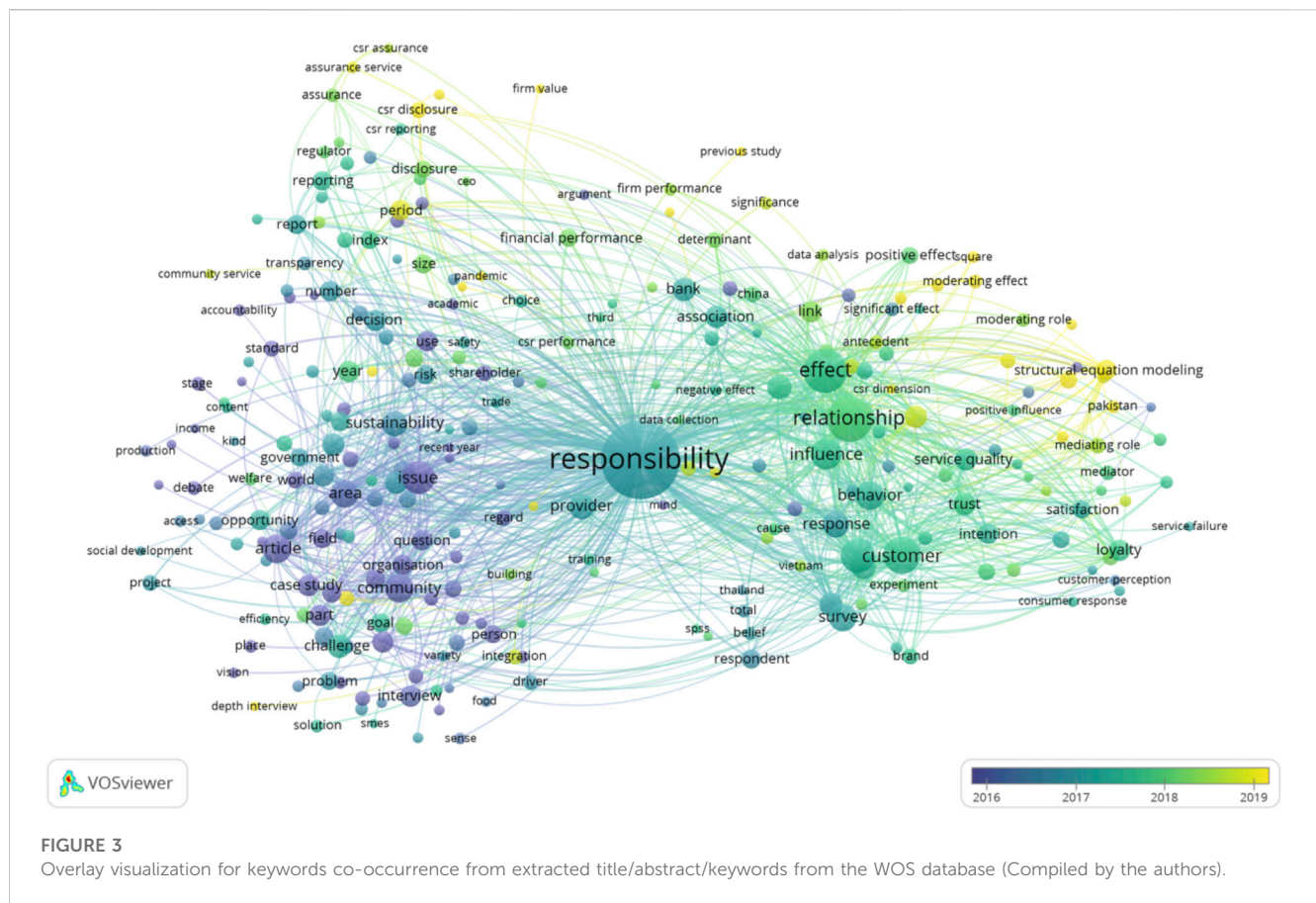
Using the WOS database and VOSviewer, the co-occurrence density map of CSR investigations published between 2001 and 2022 is shown below. Throughout the graph, terms with stronger scientific keyword linkages are depicted as linking nearer together, whereas the keywords of weaker correlations are further apart. In addition, the occurrence of a term in the central circle of the co-occurrence map showed the significance of that node in the keyword's shared platform. In addition, the most frequent terms used in CSR papers are displayed in the following diagram. As seen, the size of the circle indicates further applications of the idea or

TABLE 6 Keywords co-occurrence shown to verify its frequency and linkage strength (Compiled by the authors).

Keywords	Occurrence	Total link strength
Corporate social responsibility	488	494
Sustainability	108	137
Sustainable development	65	103
Service sector	46	77
Service quality	32	67
Perception	31	81
Financial services	29	70
Corporate strategy	28	61
Ethics	28	44
Customer loyalty	25	52
Stakeholder	25	69
Economic and social effects	23	61
Customer satisfaction	22	47
Banking	22	51
Financial performance	22	46
Consumption behavior	19	49
Corporate governance	19	26
Strategic approach	17	50
China	16	30

keyword. As indicated in the graph, the most often used terms were CSR (shown with responsibility), impact, connection, customer, influence, sustainability, community environment, and management (see Figure 3 below). A more interesting judgement to such findings is to centralize the concept of "sustainability", in which Pazienza et al. (2022) defined as corporate sustainability.

To further elaborate the detailed keywords frequency, the authors then collected the filter by keyword panel data in the following table. Frequencies that are included in a percentage up to a specified measurement range are added together to get the cumulative frequency (Winkler, 2021). The statistics are shown in the form of a table above (See Table 6), within which the occurrences are broken up into several sections based on the categorical variables. In the process of keyword selection, there are 2,854 keywords shown in the VOSviewer software. The authors selected the minimum number of occurrences of a keyword is 15 times of frequency. Then, the authors set number of keywords to be selected as 25, of which the total strength of the co-occurrence links with other keywords can be calculated. Finally, the verified selected keywords shown as follows. Afterwards, the authors merged the duplicated phrases or keywords. For instance, the keywords "stakeholder (23)", "stakeholder theory (19)" and the "stakeholders (16)" are merged together as occurrence = 58, because they identified the same meaning. Furthermore, if corporate social responsibility, CSR, corporate social responsibility (CSR) are shown, the latter two phrases are merged into the first phrase.



Discussions

How has studies on CSR in the service industry grown during the past 3 decades? To address such issue, the prominent publications were summarized with unique time periods-based groups in the following Table 7. Using MS Excel software, top of the finest articles is then selected and presented in the statistics below. The assessment of the publications revealed an increasing importance to the conceptualization, perspectives and methods over the CSR strategy in the service sector between 2001 and 2023. CSR has made significant progress throughout business communities, cooperate orientations and governance (Gull et al., 2022). Ecologic assertiveness and advancements (Araujo da Costa et al., 2020), providing environmentally-friendly services and responsible commodities (Latapi Agudelo et al., 2020), emissions (Fukuda & Ouchida, 2020), service with virtues of humanity (Rhou & Singal, 2020), and customer-friendly operational processes (Cha et al., 2016), have been highly referenced during the aforementioned time period. Consequently, some of the finest studies written during this time period addressed the determinants, consequences and benefits of CSR in the service industry in a metaphorical sense (Boubakri et al., 2021).

The service industry, including tourism and hospitality enterprises, is subject to the identical repercussions that CSR has on the subject of customer choice. Through the current systematic review in service businesses such as travel agencies and hotels, it has been shown that the fundamental variables that influence customers'

behavior, which include consumer loyalty (as shown above in the keyword occurrence), purchase intent, intrinsic motivation, and confidence in tourism companies (Bagga & Bhatt, 2013; Meitiana et al., 2019; Rodríguez et al., 2022). In addition, customer identification of the firm will facilitate the development of a strong consumer-business connection and encourage consumers to make purchases (Bhattacharya & Sen, 2004). As a consequence of this, it is essential to improve the reputation and image of a service business by formulating relevant CSR initiatives (Esen, 2013; Kim et al., 2020).

Therefore, corporate social responsibility is of utmost importance for service businesses in the current social circumstances. Even if there are a great number of other studies that investigate CSR and the service sector these papers are characterized by having an inadequate scope, and as a result, they are unable to give a thorough knowledge of CSR and the role of CSR stakeholders (Camilleri, 2015; Estol et al., 2018). Bravo et al. (Bravo et al., 2012) describe CSR as the whole of a company's responsible customer-focused actions. CSR encompasses the services and attitudes a business delivers to its consumers in their thoughts, its connection with its customers, its code of ethics, and the fulfillment of its pledges to its customers (Carroll & Shabana, 2010).

Brand loyalty was one of the criteria that determined an consumer's purchase intention, which demonstrated that customers' faith in a company's overall image could be affected by the business's dedication to CSR (Bhattacharya & Sen, 2004). A

TABLE 7 The most cited papers (Summarized by the authors).

Number	Authors names	Title	Year	Journal	Citations
1	Brammer S., Millington A., Rayton B.	The contribution of corporate social responsibility to organizational commitment	2001	Journal of Consumer Marketing	744
2	Lantos G.P.	The boundaries of strategic corporate social responsibility	2009	Journal of the Academy of Marketing Science	630
3	Vlachos P.A., Tsamakos A., Vrechopoulos A.P., Avramidis P.K.	Corporate social responsibility: Attributions, loyalty, and the mediating role of trust	2013	Journal of Banking and Finance	519
4	Wu M.-W., Shen C.-H.	Corporate social responsibility in the banking industry: Motives and financial performance	2015	International Journal of Production Economics	352
5	Chae B.	Insights from hashtag #supplychain and Twitter analytics: Considering Twitter and Twitter data for supply chain practice and research	2011	Journal of Business Ethics	309
6	He H., Li Y.	CSR and Service Brand: The Mediating Effect of Brand Identification and Moderating Effect of Service Quality	2014	Journal of Marketing	303
7	Korschun D., Bhattacharya C.B., Swain S.D.	Corporate social responsibility, customer orientation, and the job performance of frontline employees	2005	Business Horizons	278
7	Werther Jr W.B., Chandler D.	Strategic corporate social responsibility as global brand insurance	2018	Journal of Business Ethics	225
9	Platonova E., Asutay M., Dixon R., Mohammad S.	The Impact of Corporate Social Responsibility Disclosure on Financial Performance: Evidence from the GCC Islamic Banking Sector	2015	Auditing	219
10	Cohen J.R., Simnett R.	CSR and assurance services: A research agenda	2011	Journal of Services Marketing	214
11	Mandhachitara R., Poolthong Y.	A model of customer loyalty and corporate social responsibility	2014	Journal of Economic Behavior and Organization	200
12	Mallin C., Farag H., Ow-Yong K.	Corporate social responsibility and financial performance in Islamic banks	2012	International Journal of Hospitality Management	193
13	Lee Y.-K., Kim Y.S., Lee K.H., Li D.-X.	The impact of CSR on relationship quality and relationship outcomes: A perspective of service employees	2015	Auditing	191
14	Casey R.J., Grenier J.H.	Understanding and contributing to the enigma of corporate social responsibility (CSR) assurance in the United States	2013	Journal of Services Marketing	183
15	Choi B., La S.	The impact of corporate social responsibility (CSR) and customer trust on the restoration of loyalty after service failure and recovery	2007	International Journal of Human Resource Management	179

company's corporate social responsibility (CSR) is, in point of fact, beneficial to the enhancement of the company's brand value, and the company's brand may affect the behavior and attitudes of consumers. At the current time, the notion of trust in a brand has become more prevalent in the hospitality sector (Khanlari et al., 2016; 2016; Thao, 2018; Wang, 2022; Xu et al., 2022). Trust in a destination's brand has been demonstrated in a number of studies to be an important factor in increasing visitor loyalty and fostering long-term, solid connections with travelers (Aliffianto & Candraningrat, 2018). Trust in a brand, which is the core of the value that a brand delivers to its customers, may have an effect on the attitudes of those customers.

More than ever before, companies engage in CSR initiatives to make a positive contribution to society or support their strategic goals (Skarmas & Leonidou, 2013). Furthermore, they further illustrate the technique by using the empirical dataset in study on consumer skepticism about corporate social responsibility (CSR) (Skarmas et al., 2014). Although consumer skepticism about corporate social responsibility (CSR) is on the increase, research

on the psychological dynamics of skepticism is limited, especially when CSR communication acts as a company's crisis response plan. Thus, the current study proposes that Corporate Social Responsibility (CSR) practices may influence consumers' pro-social behavior. Mantovani et al. (2017) propose that this influence depends on the firm's motivation for CSR, and is moderated by the consumer-brand social distance. Lee examine the impact of Twitter followers and consumer skepticism on issue support behavior advocated in Twitter-based corporate social responsibility (CSR) communication (Lee et al., 2018). The purpose of Arli's study is to investigate the impact of corporate hypocrisy and customer skepticism on the perception of company reputation (Arli et al., 2019). Newman attempts to explain how to lessen consumer CSR skepticism by evaluating the gender and gender-related aspects of a corporate spokesman (Newman et al., 2019). Using two between-subjects design studies, Ham and Kim (2020) examine the effect of consumer CSR skepticism in consumer responses to CSR messaging during various kinds of crises.

The research of Shankar et al. examines the effect of corporate social responsibility (CSR) domain on brand relationship quality (BRQ) among millennials (Shankar & Yadav, 2021). Thus, the research of Dalal describes the causes and effects of CSR skepticism (Dalal, 2020). Lasarov et al. (2021) add to the CSR literature by presenting an overlooked but significant variable that helps explain why consumers sometimes respond favorably and sometimes adversely to CSR communication. So much of this literature helps me to comprehend the academic community's present research development, enabling me to seek a better degree of research outcomes in the coming years.

Conclusion

This article is intended to outline the most important issues in the field of CSR in the service industry through a systematic review approach in light of the material offered in the WOS debate platforms from as early as 2001 to the most updated year of 2023. According to the research findings, the managerial enlightenment offered to the service businesses by this study has been proposed and categorized. Concluding comments and recommendations are further proposed. The following sections identify the theoretical significance, practical contributions and the existing limitations of the current investigation.

Theoretical significance

Service businesses should make use of their corporate social responsibility programs to encourage the growth of sustainable development as an essential component of service industry development. This research contributes to the expansion of the research viewpoint of corporate social responsibility from the point of view of both CSR and researchers. In addition to the above, the study develops a more methodical theoretical model within the framework of branding, and it makes use of brand trust as an intermediate variable in order to broaden the theoretical research on CSR approach.

Practical significance

The service industry is often regarded as having several detrimental effects on the natural environment (de Grosbois, 2012; 2016). A crisis of confidence posited by the COVID-19 pandemic in the travel sector has resulted from the unfavorable hot search of travel businesses. As the notion of sustainable tourism grows and customers become more environmentally conscious, it has become a challenge for travel businesses to attract these client groups and satisfy their environmental demands (Moyeen et al., 2019). By analyzing the CSR initiatives, the operators and management of the service company may reappraise the significance of CSR, allowing them to proactively engage in CSR. In addition, the utilization of CSR concept to gain consumer support offers the service firms with a fresh marketing viewpoint for achieving economic rewards.

Future research agenda

The existing research gaps are then fulfilled through the current systematic review, which may be interpreted as an encouragement for further study. After comparing it to past findings, we are able to determine a future research agenda, which is also another way to identify the limitations. This must be investigated into a broader scope of disciplines, for instance, in decision sciences and other areas. Corporate Social Responsibility has proved both its high worth and rapidly expanding importance in the global service industry. Firstly, provided that CSR is primarily is an environmental, business and enterprise subject, there exists an obvious necessity to investigate the difficulties in the strategy-oriented perspective and a practical implication. Second, comprehensive study via the perspectives of a comprehensive manner, challenges will help regulators and decision-makers combine varied policy agendas and establish well-defined policy objectives. Third, it is important to recognize that a striking difficult to address the challenges of CSR and regular strategic choice through a cost-benefit input by the enterprises. Last but not list, ESG (Environmental, Social, and Governance) and (Corporate) Sustainability are new proposals or acronyms that span the CSR domain that have emerged in recent years, mostly from a management viewpoint. The study of this article indicates the ESG or Corporate Sustainability as one of the most often occurring terms we may be able to explore this convergence in the course of further studies. Thus, as the worldwide monetary and policy environment continues to evolve, it is anticipated that new difficulties may emerge to the service sector. In addition, to the best of our knowledge, no comprehensive study of relevant literature is currently accessible. It is undoubtedly worthwhile to investigate and compare the results of the current bibliometric investigation.

Author contributions

JJZ: conceptualization, framework of the manuscript, and first draft preparation. LS: conceptualization, supervision and review and editing. ZYL, XPS and XCZ: conceptualization and review and editing. All authors contributed to the article and approved the submitted version.

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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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Can senior executive characteristics improve carbon emission performance? Evidence from China

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In recent years, the backbone of China's market economy has involved controlling corporate carbon emissions and reducing environmental pollution. This study aimed to investigate the relationship between the characteristics of senior managers and the carbon emission performance of enterprises. The empirical study used panel data on high-emission industries operating in the China A-shares market from 2014 to 2017. The results showed that the natural age, education level, and professional background of senior managers in high-emission enterprises were negatively correlated with the carbon emission performance of enterprises. However, in the case of large enterprises, there is no strong relationship between the natural age of executives and carbon emission performance, while professional background and education level are negatively correlated with carbon emission performance. However, natural age is significantly related to carbon emission performance in small and medium-sized enterprises. In the regional classification of enterprises, the natural age and professional background of the core executives of high-emitting enterprises in the eastern region are negatively correlated with carbon emission performance, while the professional background of the core executives of high-emitting enterprises in the central and western regions is positively correlated with carbon emission performance. Moreover, the natural age and educational level of executives are negatively correlated with carbon emission performance. To measure the carbon emission performance of an enterprise, the study used the balanced scorecard evaluation system (CEP). Meanwhile, it innovatively classifies and sorts the sample companies based on their overall size and distribution area, and analyzes the carbon performance and executive characteristics from two perspectives. The study provides suggestions and countermeasures for companies in China, especially those in high-emission industries, to help reduce pollution.

KEYWORDS

environmental governance, executive characteristics, pollutant emission, enterprise performance, environmental pollution

1. Introduction

As an important part of corporate governance in the production and operation of a firm, management undoubtedly controls, to a large extent, decisions related to the firm, either directly or indirectly by influencing controlling shareholders. Since the introduction of higher-order theory in 1984, numerous studies have found that managers of firms have different behavioral choices and psychological characteristics depending on their background characteristics, which affect their decisions and performance, including the performance of corporate environmental protection. From this perspective, corporate socially responsible behavior can be predicted using certain characteristics of the executive team, such as age, education, tenure, and gender (Arslan et al., 2022). Elsayih et al. (2021) used the average age of the executive team as an independent variable of the study in a comprehensive industry sample and found a significant positive relationship with corporate economic performance indicators. In terms of education, Ding et al. (2020) demonstrated that CEOs with MBA degrees can significantly contribute to corporate carbon emissions. In terms of professional background, Fan (2016) found that executives with management training and business education can promote environmental pollution prevention behaviors and improve corporate carbon performance. Some scholars have also studied the factors affecting carbon emission performance at the macro level. Li et al. (2021a,b) showed that economic growth and economic structure are the most important positive and negative factors affecting carbon emissions. Liu (2023) found that, under the carbon neutral scenario, carbon emissions can be better controlled through carbon neutral and carbon peak strategies.

Most scholars still focus on the relationship between executive team characteristics and corporate financial performance, but pay less attention to this area of corporate social responsibility. The available research results show that research on carbon emission performance is still limited to the impact of differences in property rights on the results, but does not further expand the research system to the scale and spatial area of the enterprise. In addition, the research on the relationship between core management characteristics and carbon performance has not yet been unified, and there is a lack of research specifically focused on enterprises in specific high-emission industries in China.

This study focuses on companies in China's high-emission industry and innovatively classifies and sorts the sample companies based on their overall size and distribution area to analyze their carbon emission performance and executives' characteristics from two perspectives, which broadens existing research ideas. In addition, to measure the carbon emission performance of corporate management dimensions from multiple perspectives, we designed a balanced scorecard evaluation system (CEP) that is intended to fill gaps in existing literature related to the CEP evaluation system. This study can provide more reasonable and effective suggestions for the setting of core management personnel in terms of controlling the carbon emission performance of enterprises and helping listed companies in China to make greater contributions to protecting the environment and reducing emissions.

The structure of the article is arranged as follows: Section 2 presents the research hypothesis based on the literature review, Section 3 presents the research design, Section 4 presents the

empirical results and analyses, and finally, Section 5 presents the corresponding countermeasure analysis based on the summary of the empirical results.

2. Theoretical analysis and research hypothesis

Age is the most basic statistical characteristic of a person. With the accumulation of social experience and management experience, older executives are more stable and even conservative, tend to be more risk-averse, generally act strictly within the legal and even ethical framework, and therefore actively assume social responsibility. Related research has shown that, as people get older, they pay closer attention to environmental issues and have more positive environmental awareness and behavior. As people grow older, their moral evaluation standards will also increase. Therefore, older executives have more mature moral values compared to younger executives. Based on Maslow's hierarchy of needs theory, Ferrat (2021) found that, as CEOs grow older, their sense of responsibility to society will gradually increase and they will be willing to take on more social responsibilities. Second, increasing age brings more experience accumulation; compared with younger executives, older executives have more accumulated experience and are more adaptable in the face of the increasingly tightening regulatory environment (Li et al., 2021a,b). Huffman and Hegarty (1993) study demonstrated that, as the age of a chairperson grows, the quantity and quality of the frequency and disclosure of corporate environmental information increases. As the difference between the age of executives and the average age increases, the level of corporate environmental information disclosure increases accordingly (Chu et al., 2021).

In contrast, from the perspective of the size of enterprises, with the expansion of assets and the rapid increase of business revenue, the public opinion and regulatory environment in which the social responsibility and ethical awareness of enterprises are located are becoming more stringent. Therefore, large enterprises with more sound management modes and management systems will pay more attention to management experience and management stress resistance than small and medium-sized enterprises, thus resulting in the relationship between the natural age of executives and the carbon performance of enterprises. Simultaneously, owing to the different geographical conditions in the eastern, central, and western regions of China, there are obvious differences in the economic development strengths, the modes of management, and the philosophy of enterprises; moreover, there may be differences in the awareness and ability to fulfill social responsibilities. Specifically, due to its unique advantages in transportation, material distribution, and information exchange, the eastern region attracts more entrepreneurs of different ages and experts in related fields, who use more advanced international management experience to create value for the company and become the main source of China's economic development. On the contrary, due to the limitations of talent exchange and economic development, enterprises in the central and western regions tend to be more conservative in the selection and deployment of management personnel and pay more attention to management experience; hence, age is more likely to be the main consideration in management staff selection.

Therefore, we assume that:

Hypothesis 1 (H1a). Corporate carbon performance improves as the natural age of public company executives increases.

Hypothesis 1 (H1b). The relationship between the natural age of senior managers and carbon performance is stronger in large firms than in SMEs.

Hypothesis 1 (H1c). The relationship between the age of core senior managers and carbon performance is stronger in firms in the midwest than in those in the east.

It is generally presumed that the education level can reflect the cognitive ability of an individual and that it has a positive relationship with learning power, insight, and information processing ability. Executives with higher education levels can still maintain a clear mind in the face of a complex market environment, which is conducive to making correct decisions. In addition, the accumulation of knowledge brought by education provides executives with more macro-awareness and big-picture awareness in management, as well as a stronger sense of responsibility. Therefore, they generally consider various factors, such as corporate, stakeholders, consumers, and society, before making decisions. Cui et al. (2022), after a practical survey, found that, from the perspective of fulfilling social responsibility and environmental obligations, better-educated executive teams and higher-educated executive teams manage companies that have a greater chance of success in implementing corporate reforms, bringing better reputation, and providing corporate growth ability to the company. Higher levels of education lead to greater awareness of ethics and social responsibility. This motivates better-educated people to make higher-quality environmental disclosures (George Wilson et al., 2015). Chinese scholar Fu (2017) found a significant positive correlation between entrepreneurs' education and CSR disclosure status based on a survey of private enterprises in Zhejiang province. Gjerløv-Juel (2019) found that well-educated managers were more likely to make decisions concerning taking up jobs, receiving services, and buying shares and that they would consider the company's reputation, business ethics, and social responsibility and hence would be more likely to disclose high-quality environmental information. Guo et al. (2019) argued that the higher the education level, the more rational and objective executives would be in making decisions, and those with higher education levels and higher social status compared to others would be more concerned about issues such as environmental protection and food safety. Han (2019) found that the higher the proportion of executive team members who had graduated from prestigious universities, the better the CSR performance.

Compared with small and medium-sized enterprises, large enterprises have a larger base of assets, revenue, and net profit and grow faster. Therefore, they are more strict and cautious about the educational requirements of staff and the selection of management personnel. In addition, they also have obvious advantages in terms of corporate reputation, employee welfare, and business sustainability compared with small and medium-sized enterprises, using which they can attract managers with higher education levels to participate in corporate governance. From the layouts of various enterprises in different regions of China, the eastern region is

in a more prominent position in the country in the fields of transportation and human communication, and coupled with its higher level of economic development and regional tolerance, it also provides more favorable prerequisites for enterprises to attract high-level talents. Thus, the proportion of high-level talents with postgraduation or above in the overall management of enterprises is higher in the eastern region than in any other region.

Based on the above analysis, we make the following assumptions:

Hypothesis 2 (H2a). As the level of education of executives of listed companies increases, the carbon performance of companies will improve.

Hypothesis 2 (H2b). The relationship between the educational level of senior managers and carbon performance is stronger in large enterprises than in small and medium-sized enterprises.

Hypothesis 2 (H2c). The relationship between the educational level of core senior managers and carbon performance is stronger in the eastern region than in the central and western regions.

Executives with higher education, especially those with management backgrounds, are also usually more focused on long-term benefits and future development prospects than senior managers of other professions and are not easily moved by short-term interests; although environmental governance has higher short-term costs, it has higher long-term economic and social performance, and corporate managers with long-term vision usually put more attention on corporates. Haselhuhn et al. (2022) found that CEOs with MBA degrees showed significantly higher carbon performance than CEOs without academic backgrounds in 482 companies listed on the New York Stock Exchange. Li et al. (2021a,b) demonstrated that executives with a master's degree in business administration had a more significant positive impact on corporate carbon performance than those with other professional backgrounds; simultaneously, highly educated executives paid more attention to corporate environmental pollution issues and were more motivated to improve corporate carbon performance than executives with a lower education level (Li et al., 2020). Liang (2019) investigated the relationship between professional education and students' learning ability and found that management education promotes the improvement of cognitive ability, innovation ability, judgment ability, and values (Li, 2019).

With the increasing connection between enterprises in modern society, the internal control system and the financial system required by large enterprises must be more stringent than those of SMEs due to the complexity of their business. Influenced by the training program and curriculum, executives whose professional background is in finance and management have a clear advantage in the theoretical foundation and practical experience of business management compared with others. At the same time, due to the influence of the human environment and economic layouts in the eastern region, the number of financial enterprises is higher and is attracting more management talents. However,

the western region, where heavy industry is the main focus, mainly attracts engineering-based talents to enhance and upgrade the technical strength of enterprises, accelerate the efficiency of industrial production, and create higher value for enterprises, thus paying more attention to senior managers from engineering backgrounds.

Hypothesis 3 (H3a). Corporate executives with economics and management majors perform better in terms of corporate carbon performance.

Hypothesis 3 (H3b). The relationship between the professional background of senior managers and carbon performance is stronger in large companies than in SMEs.

Hypothesis 3 (H3c). The relationship between the professional background of core senior managers and carbon performance is stronger in the eastern region than in the central and western regions.

3. Research design

3.1. Data sources and sample selection

Regarding the definition of high-emission industries, reference is made to the “Guidelines for Disclosure of Environmental Information of Listed Companies (Draft for Comments)” issued by the Ministry of Ecology and Environment in 2010, and according to the 2012 edition of the SFC’s “Guidelines for the Classification of Listed Companies by Industry”, 16 categories of industries, including thermal power, iron and steel, cement, electrolytic aluminum, coal, metallurgy, chemical, petrochemical, building materials, paper, brewing, pharmaceutical, fermentation, textile, tannery, and mining, are classified as high-emission industries. Due to the limitation of space and research time, this study intends to use the 2014–2017 data from the extractive industry, the coal industry, and the chemical industry as the research samples of listed companies in high-emission industries in China and exclude other abnormal samples such as incomplete data, ST or *ST, and long-term negative equity to get 30 valid samples. The data of the independent variable CEP were all collected manually. The data on whether the enterprises have obtained ISO14000 environmental management standard certification were taken from the official website of CNCA (China National Certification and Accreditation Administration) and the data on environmental pollution were from the Public Environment Research Center. In addition to the above-mentioned websites, the annual reports of enterprises and social responsibility reports were also used. “ISO14000,” “environmental protection system,” “environmental training,” and other keywords were searched to supplement the data in this study. Meanwhile, the data related to the main characteristics of the executives of listed companies and corporate financial indicators were obtained from the CSMAR database and Sina Finance to ensure the integrity and fairness of the data. Table 1 shows the carbon emission performance evaluation system based on BSC.

3.2. Variable design

3.2.1. Explained variable declaration

Carbon emission performance is the main object of this study and the specific measurement indexes that are mainly referred to are the carbon emission performance assessment standard developed by the International Organization for Standardization (ISO) in 1999 according to the ISO14031 system, which provides a reference basis for organizations to carry out internal environmental management and carbon emission performance assessment. The ISO 14031 standard does not define specific carbon performance indicators but rather provides a structural framework. Based on the environmental protection philosophy and environmental protection system, this study innovatively develops a set of accounting systems for corporate carbon emission performance indicators, mainly from the perspective of the environmental protection strategy of the management of companies. Specifically, we compiled the annual reports and social responsibility reports of enterprises and then filtered out eight dimensions based on the principles and framework of the balanced scorecard. These eight dimensions were used to examine the carbon emission performance of the management of enterprises. Table 2 provides a description of the variables used. The specific evaluation system and the corresponding criteria are as follows.

3.2.2. Explanatory variables

Ethical growth is often accompanied by age, experience, and risk appetite stabilization. In an empirical study, Lin and Zhou (2021) found a negative relationship between executive team age and CSR (corporate social responsibility reporting) disclosure, but it did not pass the significance test. In a study of the influence of executive team characteristics on CSR information disclosure, Liu et al. (2022) found that there is a significant positive correlation between the age and education of the executive team on CSR information disclosure. As age and experience increase, managers are satisfied with the process of accumulation of money and power, and there may be a tendency to weaken the pursuit of it. Instead, they are more enthusiastic about reputation and spiritual realization and thus focus and fulfill more on CSR. Ma and Chen (2022) found that the older the average age of the executive team, the better the corporate social responsibility performance. Similarly, a study by Zhang et al. (2022) found that the proportion of executives’ age over the average age is positively related to the performance of the environmental responsibility disclosure system; the older the executive age, the better the firm’s carbon performance. The logarithm of the average natural age (AGE) of the independent variable firm executive characteristics is used as the main indicator in this paper.

Education level affects an individual’s perceptions, values, and behaviors. Highly educated executives are more concerned about the long-term benefits and prospects of the company, the realization of their self-worth, and the interests of multiple parties such as consumers and community members. Meng and Yang (2017) used empirical methods to investigate the relationship between the intensity of corporate environmental R&D investment and corporate performance, which was positive in firms with

highly educated managers and negative in firms with less educated managers. [Qin \(2012\)](#) argued that, as the social capital possessed by corporate executives and the education level of the firm continues to increase, the firm can obtain better results in terms of carbon performance. The independent variable in this study is the average educational level of the company's executive team (EDU), which is used as the main indicator, where "2," "3," "4," and "5" are used in this study according to the level of education. "2," "3," "4," and "5" are used as proxies for the company's senior executives' specialist degree, bachelor's degree, master's degree, and doctoral degree, respectively, to facilitate the regression study of panel data. The professional background reflects the level of professional qualification or competence of the executive. Compared with other professional backgrounds, managers with professional background in management may be more adept at making the most appropriate decisions for the enterprise even under the complex economic environment and tend to have a higher sense of social responsibility based on the basic goal of corporate profitability: paying more attention to the green development of the enterprise and pursuing the long-term benefits of the enterprise. [Li \(2019\)](#) selected some enterprises in China's electronic information industry as a sample and reported that the professional background of members was significantly and positively related to corporate performance. [Kang et al. \(2011\)](#) found that executive background characteristics such as age, years of service, professional background, and career experience can have an impact on managerial style, which affects corporate environmental efficiency indicators. The independent variable in this study is the average professional background of the company's executive team. Using (PRO) as the main indicator, considering that the professional backgrounds of executives in the sample data are mainly concentrated on engineering, economics, and management, according to the degree of similarity with management disciplines, "1," "2," and "3" were used as proxies for the professional backgrounds of the company's executives in engineering, economics, and management.

3.2.3. Control variables

Compared with small and medium-sized enterprises, large enterprises require more social resources and obtain greater economic benefits, while facing more political pressure and the need to assume greater social and environmental responsibilities ([Yu et al., 2017](#)). The larger the company and the better its performance, the more media scrutiny and public attention it receives and the more resources it has to improve its carbon emission performance ([Wu et al., 2018](#)). [Chen et al. \(2022\)](#) analyzed that the environmental regulation index plays a significant role in promoting green development. Investors of companies are deeply concerned about the financial performance of companies, and the degree to which a company pays attention to environmental issues depends largely on economic performance ([Yang et al., 2022](#)). In general, the higher the economic performance, the stronger the awareness of the social responsibility of the company and the more motivated it is to improve its carbon emission performance ([Tian et al., 2020](#)); simultaneously, changes in macroeconomic factors will also have an impact on the carbon emission performance of the company. Moreover, from the perspective of the production

method, as the gross domestic product increases, the overall production capacity and the actual annual output value of society will also increase, and the attention of consumers and regulators to the social responsibility of listed companies will also increase, thus indirectly urging and accelerating the management of enterprises to further set up programs and plans to control carbon emission performance. [Shao et al. \(2022\)](#) found that social media legitimacy pressure significantly enhances corporate carbon disclosure. However, enterprises with better business performance are generally more willing and able to fulfill social responsibility; therefore, a company's operating income and return on net assets may have an impact on the carbon emission performance of enterprises; the value added of the secondary industry, mainly traditional manufacturing, will have an impact on the carbon emission performance of enterprises. [Ying et al. \(2022\)](#) found that the tightening of environmental regulations had a significant net negative effect on the innovation behavior of heavily polluting firms, with a significant decrease in their innovation inputs. The value added of the secondary industry, mainly traditional manufacturing, and the proportion of the number of employees in the total industry reflect, to a certain extent, the proportion of high-emission enterprises in the total business entities. Based on this, the initial indicators of firm size, total operating income, operating income growth rate, total net asset margin, real GDP, the proportion of secondary industry and consumer price index, and the stated year are used as control variables in this study.

3.3. Model construction

This study investigates the relationship between the carbon performance of companies and the characteristics of company executives, such as age, professional background, and education level, and analyzes the influences of executive characteristics on the carbon performance of listed companies in the high-emission industry through a multiple linear regression model based on the research hypothesis and other factors that may affect the dependent variable of the model. The model is as follows:

$$CEP = \beta_0 + \beta_1 AGE + \beta_2 EDU + \beta_3 PRO + \beta_4 TEN + \beta_5 BI + \beta_6 ROA + \beta_7 GRO + \beta_8 SIZE + \beta_9 GDP + \beta_{10} PSI + \beta_{11} TPP + \beta_{12} CPI + \beta_{13} PPI + \varepsilon \quad (1)$$

where β_0 represents the constant term of the model; $\beta_1 - \beta_{13}$ are the regression coefficients of the model, and the sign of the coefficient represents the direction of the correlation between the independent variable and the dependent variable. ε is the random disturbance term of the regression model.

4. Empirical research

4.1. Descriptive statistics

[Table 3](#) describes and analyzes the extreme value, mean, and fluctuation of the dependent variable (carbon emission performance) and the independent variables (natural age, education level, and professional background) in the sample panel

TABLE 1 Carbon emission performance evaluation system based on BSC.

Dimension of consciousness	Social responsibility report	If pass, add 1 point; otherwise, add 0 point
Institutional dimension	Environmental protection concept	If pass, add 1 point; otherwise, add 0 point
	ISO14000	If pass, add 1 point; otherwise, add 0 point
	The management system	If pass, add 1 point; otherwise, add 0 point
Education dimension	The environmental protection department	If pass, add 1 point; otherwise, add 0 point
	Environmental education	If pass, add 1 point; otherwise, add 0 point
Risk dimensions	Risk response	If pass, add 1 point; otherwise, add 0 point
	Emergency treatment	If pass, add 1 point; otherwise, add 0 point

On this basis, it is concluded that CEP, the aggregate score/theoretical optimal score of the enterprise (8 points).

data regression model: the maximum value of carbon emission performance is 1.00, the minimum value is 0.13, and the mean value is 0.63, thus reflecting that the difference between different companies in carbon emission performance is still very high and that the proportion of companies with higher carbon emission performance is also very high in the whole. The standard deviation of this variable is 0.21, which indicates that even among companies in the same or similar industry, the amount of emission of pollutants may vary due to the differences in the types of products produced, production processes, production procedures, and management's attitude toward social responsibility. The minimum value of the independent variable is 41 years old and the maximum value is 60 years old. The average age is close to 53 years old, with a standard deviation of 3.86 years, indicating that the average age of the executive team in the sample data is generally around 40–60 years old. In general, managers in this age group are in the golden period of personal development, in terms of management experience, professional reserve, social experience, and stress resistance, and are also the more prominent in the team and organization. The average education level is roughly 3.92, while the standard deviation is only 0.66, which indirectly reflects that the senior management of the sample companies is generally at master's degree level. The average value of professional background of the sample data is 1.71, while the standard deviation is 0.88, which indicates that employees with professional backgrounds in economics and management are more likely to become the main managers of the company. Regarding the macroeconomic factors, the minimum value of GDP is 641,286,000 yuan and the maximum value is 820,743,000 yuan, which indicates that there is still a large gap between the different annual GDP, which will be one of the main factors affecting the dependent variable. Meanwhile, the minimum value of the producer price index (PPI) is 94.8 and the maximum value is 106.3, which indicates the operating cost of enterprises in different time periods. Second, the standard deviations of operating income and total asset size are 1.47 and 1.28, respectively, while the mean values are roughly

23.32 and 24.29, indicating that the difference between the sizes of the business scale of enterprises in the same industry is not very obvious.

4.2. Analysis of regression results

As can be seen from Table 4, the overall significance of the model is 27–28% and the p -value is <0.01 , indicating that the overall significance of the model is strong and the fit is good. Under the fixed-effects model, the regression coefficient of the natural age of executives is -0.006 and it is significant at the 5% level, indicating a negative relationship between the natural age of executives and carbon emission performance. It is the opposite of original hypothesis 1, indicating that as the age of executives grows, they become more conservative in their perceptions, and those with longer tenure may prefer to maintain their original system and achievements compared to making contributions to the environmental protection cause, and therefore, may have a negative impact on the carbon emission performance of the enterprise; however, at the same time, the regression coefficients of the educational level and professional background of executives are -0.017 and -0.001 , respectively, and both are significant within the 10% level, which are different from both original hypotheses 3 and 2, indicating that the carbon emission performance of high-emission-listed companies decreases with the increase in the average educational level of the management team. However, due to the lack of technical ability and background, managers with management or economics background are more passive in the specific implementation plans and technologies of carbon emission performance control. In addition, among the control variables studied, the overall size of the enterprise and the return on net assets are positively correlated with carbon emission performance and are significant at the 5% level, indicating that they will affect the carbon emission performance to a certain extent and the larger and more efficient enterprises will be more willing and able to reduce carbon emissions. This indicates that the increase in the price of raw materials and labor will, to a certain extent, increase the operating cost of enterprises and reduce their net profit, which indirectly affects the ability and willingness of enterprises to control their carbon emission performance, while the relationship between the two is not very strong.

As can be seen from Table 5, the R^2 of small and medium-sized enterprises is higher than that of large enterprises and the goodness of fit is stronger, probably because the financial situation and profitability level of large enterprises are better than those of small and medium-sized enterprises, in general. However, unlike the lack of liquidity of enterprises, the main bottleneck that restricts the development of small and medium-sized enterprises, the main dilemma faced by large enterprises is the competitive pressure of international technology and industry. From the specific regression results, the correlation coefficients between the natural age of the executive team and the carbon emission performance of large enterprises tend to be close to 0, indicating that natural age is not the main factor affecting the environment; however, the correlation coefficients between education level and professional background and carbon emission performance are -0.111 and

TABLE 2 Variable description.

Variable nature	Variable name	Symbol	Variable definition
Explained variable	Carbon emission performance	CEP	CEP collects manually according to the above methods
Explanatory variables	Natural age	AGE	General manager age
	Academic degree	EDU	Educational background of general manager
	Professional background	PRO	General manager of the highest degree major
	Tenure	TEN	Tenure of the general manager
Control variables	The company size	SIZE	The natural logarithm of total assets at the end of the year
	Operating income	BI	The natural logarithm of an enterprise's total operating income for the year
	The net interest rate on total assets	ROA	Annual net profit/(total assets at the beginning of the year + total assets at the end of the year)/2
	Revenue growth rate	GRO	Increase of operating income of the current year/total operating income of the previous year
	Gross domestic product	GDP	The gross domestic product of all industries that year
	Secondary industries	PSI	The added value of the secondary industry in the current year/total GDP of all industries in the current year $\times 100\%$
	Secondary industry employment	TPP	Total number of secondary industry employees in the year
	Consumer price index	CPI	(the value of fixed goods at the current price divided by the value of fixed goods at the base price) $\times 100\%$
	Producer price index	PPI	(the ex-factory value of fixed goods in the current period divided by the ex-factory price of fixed goods in the base period) $\times 100\%$
	Year	YEAR	Annual
	The company size	SIZE	The natural logarithm of total assets at the end of the year

TABLE 3 Descriptive statistical table.

Variable	Obs	Mean	Std. Dev.	Min	Max
CEP	120	0.6326667	0.2068683	0.13	1
AGE	120	52.975	3.857684	41	60
EDU	120	3.916667	0.6557225	3	5
PRO	120	1.708333	0.8830413	1	3
SIZE	120	23.31558	1.276234	20.25	26.24
BI	120	24.29035	1.470672	21.701	28.5087
ROA	120	0.1068517	0.3555266	-0.4893	2.4747
GRO	120	0.0228692	0.0929053	-0.443	0.1778
GDP	120	722022.2	67158.54	641280.6	820754.3
PSI	120	41.25	1.241103	40.1	43.3
TPP	120	22491.5	469.7318	21824	23099
CPI	120	101.75	0.260897	101.4	102
PPI	120	99.45	4.23342	94.8	106.3
Variable	Obs	Mean	Std. Dev.	Min	Max

-0.05, respectively, and both are significant at the 10% level, indicating that there is still a negative relationship between the main independent variables and carbon emission performance. The correlation coefficients are 0.046 and 0.006, respectively, which is mainly because, in private capital-held SMEs, the management philosophy and vision of the managers are constantly updated and broadened with the increase of their natural age (Fan, 2016).

The longer the tenure, the more they recognize the importance of strengthening their innovation ability and enhancing their R&D strengths in terms of industrial competition. In addition, the more educated the senior managers, the deeper their mastery of enterprise production and management theories and the more they pay attention to technological innovation, meaning they will improve to some extent the innovation performance. Among

TABLE 4 Regression test of executive characteristics and carbon emission performance (excluding the nature of equity and enterprise size).

The variable name	(1) CEP	(2) CEP	(3) CEP	All the samples
AGE	−0.006**			−0.007
EDU		−0.017*		−0.026**
PRO			−0.001**	−0.009***
BI	−0.009**	−0.021*	−0.019	−0.013**
ROA	0.078*	0.048*	0.058	0.059
GRO	−0.006	0	0	−0.004
SIZE	0.117**	0.1*	0.104**	0.111
GDP	0	0	0	0
PSI	(Omitted)	(Omitted)	(Omitted)	(Omitted)
TPP	0.001*	0.002	0.001**	0.001
CPI	(Omitted)	(Omitted)	(Omitted)	(Omitted)
PPI	−0.031**	−0.033	−0.032*	−0.033
_cons	−38.047	−42.721	−40.645	−40.445
r2	0.278	0.274	0.272	0.281
r2_a	−0.048	−0.054	−0.056	−0.07
N	120	120	120	120
F	3.947	3.861	3.838	3.119

***, **, * Represent the significant regression coefficients at the levels of 1, 5, and 10%.

TABLE 5 Regression results of high-carbon industry companies with different asset sizes.

	The variable name of large enterprises on innovation performance				The influence of small and medium-sized enterprises on innovation performance			
	(1) CEP	(2) CEP	(3) CEP	All the samples	(1) CEP	(2) CEP	(3) CEP	All the samples
AGE	0			0.005**	−0.046**			−0.045*
EDU		−0.111**		−0.082		0.074		0.01
PRO			−0.05*	−0.059*			0.006*	−0.012*
BI	0.174**	0.201	0.208*	0.174	0.089*	−0.025	−0.053**	0.086
ROA	−1.046*	−1.78	−1.604	−1.245*	0.382	0.275*	0.242	0.376
GRO	−0.096*	−0.105	−0.151	−0.057	0.063	0.053*	0.031	0.066*
SIZE	0.112	0.283	0.257**	0.146	0.166	0.054**	0.039	0.163
GDP	0	0	0	0	0	0	0	0
PSI	(Omitted)	(Omitted)	(Omitted)	(Omitted)	(Omitted)	(Omitted)	(Omitted)	(Omitted)
TPP	0.003**	0.001	0.002	0.002*	0	0.001*	0.001	0
CPI	(Omitted)	(Omitted)	(Omitted)	(Omitted)	(Omitted)	(Omitted)	(Omitted)	(Omitted)
PPI	−0.043	−0.016**	−0.025	−0.028*	−0.029*	−0.025	−0.029**	−0.028*
_cons	−77.943	−49.665	−63.994	−55.839	−7.877	−15.793	−25.361	−5.94
r2	0.385	0.372	0.356	0.396	0.343	0.279	0.259	0.344
r2_a	−0.133	−0.157	−0.186	−0.244	−0.024	−0.123	−0.154	−0.073
N	36	36	36	36	68	68	68	68
F	1.488	1.405	1.315	1.113	2.803	2.082	1.88	2.147

***, **, * Represent significant regression coefficients at the levels of 1, 5, and 10%.

TABLE 6 Regression results of high-carbon industry companies in different economic regions.

Name	Impact of the eastern region on carbon emission performance				Impact of the eastern region on carbon emission performance			
	(1) CEP	(2) CEP	(3) CEP	Samples	(1) CEP	(2) CEP	(3) CEP	Samples
AGE	−0.005**			−0.029**	−0.01**			−0.011*
EDU		−0.082*		−0.172*		−0.019*		−0.036
PRO			−0.02**	0.092**			0.029**	−0.022**
BI	−0.054*	−0.071	−0.064**	−0.032	0.069**	0.047*	0.056	0.067*
ROA	0.352	0.336	0.324	0.47	−0.26	−0.314**	−0.274	−0.325
GRO	0.061	0.084*	0.067*	0.081**	−0.14	−0.12	−0.127**	−0.145
SIZE	0.048*	0.007	0.035**	0.056	0.233	0.21**	0.217	0.236
GDP	0	0	0	0	0	0	0	0
PSI	(Omitted)	(Omitted)	(Omitted)	(Omitted)	(Omitted)	(Omitted)	(Omitted)	(Omitted)
TPP	0.001	0.002**	0.001	0.002	0.002	0.002**	0.002	0.002
CPI	(Omitted)	(Omitted)	(Omitted)	(Omitted)	(Omitted)	(Omitted)	(Omitted)	(Omitted)
PPI	−0.029**	−0.039	−0.029*	−0.047	−0.031	−0.032*	−0.032**	−0.031
_CONS	−30.955	−45.777	−31.828	−50.896	−48.292	−49.568	−48.81	−49.384
r2	0.304	0.322	0.303	0.349	0.414	0.4	0.403	0.416
r2_a	−0.075	−0.047	−0.075	−0.051	0.017	−0.007	−0.003	−0.055
N	72	72	72	72	48	48	48	48
F	2.508	2.73	2.504	2.357	2.475	2.332	2.359	1.854

***, **, * Represent significant regression coefficients at the levels of 1, 5, and 10%.

the control variables, the net interest rate on total assets and the size of total assets are also positively correlated with the innovation performance of enterprises, mainly because enterprises with larger capital and better economic efficiency have more economic strength and research teams to engage in scientific and technological research and development, which improve the innovation performance of enterprises. However, macroindicators such as gross domestic product and producer price index are roughly the same as those described in the previous section.

Table 6 shows the regression results from a subregional perspective. The adjusted R^2 -values of the regression results for enterprises in the central and western regions are ~40–41%, and the overall goodness of fit of the equation is better than that of the eastern region. This is probably because the eastern region has been developing for a long time and is in the late stage of high-quality economic development, technology, and innovation, which are no longer the main factors to improve the innovation performance of enterprises (Fu, 2017). In addition, due to the priority development and strong support policies of the state for the central and western regions in recent years, enterprises can enjoy various support and preferences for their investments in innovation and R&D; therefore, the management will put more effort into innovation and R&D. The regression coefficient of the main explanatory variable, professional background of executives, is 0.029, and the variable is significant at the 10% level or less, which verifies the original hypothesis 3, that is, executives with management background have a more global and long-term strategic vision in enterprise development than those with other majors. They are also more likely to focus their future core

competencies on industrial innovation and technology research and development, thus enhancing the innovation performance of the company. However, the regression coefficient of the natural age of executives is −0.01 and significant at the 10% level, indicating that the innovation performance of enterprises is closely related to the natural age of executives, i.e., the younger the natural age of senior managers in privately held companies is more likely to have a more complete awareness and view of environmental protection.

5. Discussion and conclusion

5.1. Theoretical contributions

Using the above data, the multiple linear regression model analyzed the relationship between the characteristics of executives (natural age, professional background, tenure, and education level) and the control variables of operating income and asset size, and carbon emission performance. In contrast to other recent literature, which has involved studies on the impact of macroelements on carbon performance (Zhou and Liu, 2020; Shao et al., 2022), this study focused on the micro level. The relationship between the natural age of core executives in large enterprises and the carbon emission performance of large enterprises is not strong; however, professional background and education level have a negative relationship with carbon emission performance. In small and medium-sized enterprises, natural age is significantly correlated with carbon emission performance. In the regional classification of enterprises, the core executives of high-emitting enterprises in

the eastern region are negatively correlated with carbon emission performance in terms of tenure, natural age, and professional background, while those in the central and western regions are positively correlated with carbon emission performance in terms of professional background and natural age. Moreover, the educational level of executives is negatively correlated with carbon emission performance. The findings of this study provide some important policy insights that will enable China to explore the low carbon transition of economic development and achieve the goal of carbon peaking and carbon neutrality.

5.2. Practical implications

By studying the influence of the characteristics of executives on corporate carbon performance, this study anticipates that the research results will provide ideas and methods for current regulators to formulate and introduce regulations and policies. These research findings could also help companies to effectively build and integrate their executive teams, optimize their senior governance structure, improve the resource allocation of top management, and promote sustainable development from the perspective of controlling corporate carbon performance. Therefore, we make the following recommendations in terms of laws and regulations, the internal senior management setup, and the environmental protection of enterprises.

Laws and regulations in turn have a direct impact on the environmental accounting practices of enterprises, and the environmental behavior of enterprises and the environmental decisions they make follow the provisions of the law. Although current regulations, such as the Environmental Protection Law and the Accounting Law in China, have, to a certain extent, institutionally strengthened the supervision of enterprises, especially listed companies, by environmental regulators, there is less knowledge on carbon emission performance, and there is a lack of specific standards and reward and punishment systems for carbon emission performance evaluation. In addition, due to the light penalties and the lack of responsibility of the personnel in the relevant functional departments, these laws and regulations often face difficulties in the implementation and lack of enforcement in the actual implementation process; hence, the environmental pollution problems in China are becoming increasingly widespread and serious. Therefore, China urgently needs to establish and improve a set of laws and regulations on carbon emission performance.

From the perspective of age, enterprises should give more consideration to older executives instead of blindly pursuing young management teams. From the perspectives of professional background, corporate governance, and human resources can favor executives with professional backgrounds in engineering and science when conducting management screening, which can enrich and optimize the professional backgrounds of enterprise management personnel, enhance and improve the production level and efficiency of enterprises, and improve the carbon emission performance of enterprises. From the perspective of education, since carbon emission performance will improve with the improvement of the education of senior management members, enterprises, especially the senior management of listed companies,

should improve their education level, and at the same time, enterprises should focus on the education level when selecting managers. From the perspective of tenure, the research findings indicate that appropriate transfer of business managers may affect the stability of management but it can promote the improvement of carbon emission performance to a certain extent. The transfer system of state-owned enterprises, which is now implemented in China, can strengthen the supervision of internal management and control within local enterprises and also drive enterprises to invest more in environmental protection and improve the carbon emission performance of the whole industry to a certain extent.

Improving the selection and incentive mechanism of key senior managers and reconfiguring the composition of the organization's management team in terms of their natural age, professional background, tenure, and educational level will strengthen the cohesiveness of the management team and improve the carbon performance of the enterprise, thus making an important contribution to the sustainable development of the enterprise and society.

In particular, for enterprises involved in high energy consumption and high pollution industries, both management and ordinary staff should have proper knowledge and understanding of environmental issues while pursuing the maximization of economic benefits for the enterprise to facilitate the smooth implementation of environmental protection work. Nevertheless, the government should introduce corresponding policies to encourage enterprises to vigorously cultivate or introduce environmental talents, set up specialized environmental management agencies from top to bottom, and slowly improve the carbon performance of enterprises with technological changes and professional environmental management tools. The relevant government departments should set up special institutions and personnel to regularly assess the carbon performance of enterprises in their areas of responsibility, especially the departments or main leaders of high-emission enterprises, actively accept the supervision of the public, and stop production in time and rectify the more polluting production lines. Moreover, a strict reward and punishment mechanism should be implemented, and individuals and departments with high carbon performance should be rewarded, and those with low carbon performance should be punished to make an effort at improving the carbon emission performance of enterprises.

Furthermore, to supervise the environment, it is not enough to rely only on the power of the government and enterprises. The level of environmental protection in our society depends on the strength of the environmental awareness of the members of society; therefore, it is necessary to strengthen the education of the general population on environmental protection and lay a solid foundation for environmental protection so that environmental pollution and other problems can be managed well.

5.3. Limitations and directions for future research

Finally, it should be noted that, due to the limited availability of data, this study only examined the influence of executive characteristics on carbon performance at the level of firms

in high-emitting industries. The exploration of carbon performance-related issues at other industry levels would complement research at the high-emissions industry level, thus helping firms to fully grasp key bottlenecks in the development of China's low-carbon economic transition. Therefore, a global examination of related issues at the firm level should also be an important direction to expand subsequent research.

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

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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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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