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Environmental regulation promotes green development in China: from the perspective of technological innovation

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Based on panel data of 286 prefecture-level cities in China, this study analyzes the direct impact of environmental regulation and its classified policies on green development, while exploring the indirect effects and threshold effects of technological innovation in the green development effect of environmental regulation. There are four main findings in this study. 1) The impact of environmental regulation on green development follows a U shaped pattern and its mode varies with the type of environmental regulation and the type of cities. 2) Environmental regulation can promote green development through technological innovation, and the industrial structure has a positive moderating effect. 3) Technological innovation is a threshold variable in the impact of environmental regulation on green development: when technological innovation surpasses the threshold value, the green development effect of environmental regulation changes from negative to positive. Therefore, governments should strengthen environmental regulation, effectively play the driving role of different environmental regulation policies, and transform the development driving force through strengthened technological innovation to achieve regional green development.

KEYWORDS

green development, environmental regulation, technological innovation, sustainable development, threshold effects

1 Introduction

With the rapid growth of the world economy, human beings claim resources and discharge wastes excessively, which causes severe pressure on resources and environment and poses a severe challenge to sustainable development. After the world financial crisis in 2008, facing the development dilemma, the academic community deepens the research of sustainable development and put forward green development. In 2009, Organization for Economic Co-operation and Development (OECD) defined green development as a development model that not only provides sustainable resources and environmental services for human wellbeing, but also promotes economic growth. Benefit from a balance between economic development and environmental protection, green development is one of the ways to achieve global sustainable development. As the largest developing country, China has experienced rapid economic growth for decades. However, China is increasingly facing serious economic and environmental pressures (Dong et al., 2020) due to its long-term extensive growth pattern. Therefore, it is urgent for China to follow the idea of ecological civilization and promote green development.

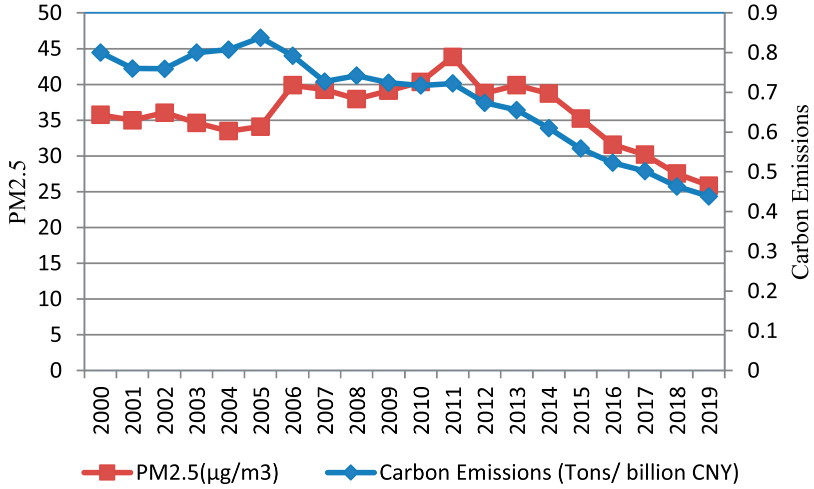

FIGURE 1
China's carbon emission intensity[1] and PM2.5[2] in 2000–2019.

There are many factors affecting green development, including urbanization, innovation capacity, industrial structure, human capital, openness, etc. All of these factors focus on green development from the perspective of the market. In contrast, environmental pollution and control have strong non-exclusive and externalities. Therefore, relying solely on the market mechanisms can not fully achieve green development, which requires the government to take measures. The historical experience of reducing heavy pollution in developed countries shows that environmental regulation can effectively control the environment and promote economic development (Zhang et al., 2021). Environmental regulation is one of the leading policy tools for the government to control pollution and protect ecology. In 1973, China issued "Protection and Improvement of the Environment Several Provisions", marking the beginning of environmental regulation. Subsequently, China issued the "The People's Republic of China Environmental Protection Law(Trial)" in 1979, marking the legalization of environmental regulation. With the improvement of the legal system, there are various types of environmental regulation policies. In 2003, China implemented the market incentive environmental regulation "Collection, Use and Management of Pollutant Discharge Fees Regulations". In 2006, China issued the first normative document of public participation environmental regulation "Environmental Impact Assessment Public Participation Interim Measures", which jointly marked the improvement of environmental regulation. Therefore, under the background of New normal of Chinese economy and high-quality development, how effective the green development of environmental regulation is and whether there are differences in the impact of different environmental regulation policies, are hot issues that people concern about and discuss.

In addition, China faces the dual goals of improving economic quality and building ecological civilization. Its strategic support is to achieve the unity of innovation-driven and green development. Innovation is the first productive force and can promote China's economic development. Figure 1 shows that China's carbon emission intensity has declined since 2005. Especially after the development of environmental regulations in 2011, effective policies have significantly reduced the intensity of carbon emissions. At the same time, the concentration of PM2.5 in China has also decreased since 2013, indicating that green development has improved. However, the decline rate of China's carbon emission intensity and PM2.5 concentration has slowed down since 2016, indicating that the efficiency of green development promotion is low[1].

China's slow transformation of new and old driving forces has led to insufficient supply of technological innovation. Lack of internal impetus for environmental protection led the low efficiency of China's green development. Relevant research shows that environmental regulation can indirectly promote green development through enterprise technological innovation (Ye et al., 2021). In order to achieve green transformation and efficiency improvement of economic development, the government needs to focus on green biased technological progress. It can be said that environmental regulation is the cornerstone of green development, and innovation-driven is the driving force of green development. In order to accelerate the green development and promote sustainable development, it is of great significance to analyze the role of technological innovation in the green development effect of environmental regulation, and then find out the path of technological innovation to promote the green development effect of environmental regulation[2].

This study aims to analyze the direct impact of environmental regulation on green development and the indirect impact of environmental regulation on green development through technological innovation. This paper tries to make contribution and innovation from three aspects. First of all, Previous studies used short-term data of micro-enterprises and industries to study the green development effects of environmental regulations, and

1 Carbon emission intensity is the carbon dioxide emission per GDP. The data is from China Emission Accounts and Datasets (CEADs).

2 The data is from the atmospheric composition analysis group of Dalhousie University.

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ignored the differences in the green development effects of environmental regulations for different pollutants and different cities. Using the panel data of 286 cities, this paper clarifies the effect of environmental regulations on green development since ecological civilization construction was proposed at the 18th CPC National Congress, and reveals the difference in the effect of a variety of environmental regulations on green development, as well as its difference for cities with different geographical locations, urban agglomerations, city sizes and pollution levels. Secondly, previous studies only clarified the intermediary role of technological innovation in environmental regulation affecting green development, ignoring the role form of technological innovation, and did not find the regulatory role of external factors. This paper discusses the threshold effect of technological innovation in environmental regulation affecting green development, clarifies the role of technological innovation degree in environmental regulation affecting green development, and identifies the regulatory effect of industrial structure. Finally, the theoretical model constructed by previous studies only discusses the impact of environmental regulation on economic growth, without involving technological innovation. This paper incorporates environmental regulation into the whole process of production, establishes a mathematical model including multi-regional environmental regulation, technological innovation and green economic output, and reveals the mechanism of the three through mathematical derivation.

The rest of this article is organized as follows: Section 2 compares the relevant literature, Section 3 constructs a theoretical model, Section 4 introduces the variables and data, Section 5 presents the empirical analysis results, Section 6 discusses the empirical results, Section 7 makes policy recommendations and points out areas for improvement.

2 Literature review

2.1 Environmental regulation affects green development

For a long time, the impact of environmental regulation on green development has been highly concerned by economists. However, there is no consensus on the existing research. Most studies support the Porter's hypothesis: moderate environmental regulation can increase corporate profits by stimulating technological progress of enterprises and improving market allocation mode, thus improving total factor productivity of enterprises (Ghosal et al., 2019; Jiang et al., 2022a). Some literature supports the "cost effect" hypothesis: environmental regulations increase pollution control costs as well as enterprise operating costs, crowd out R&D expenditure, weaken enterprise competitiveness, and even affect the transfer of regulated industries, thus inhibiting regional green development (Manello, 2017; Zhao et al., 2019). There is no doubt that both positive "Porter's hypothesis" and the negative "cost effect" hypothesis have their explanatory space. The direction of net effect depends on which is dominant. In other words, the impact of environmental regulation on green development is not linear (Ren et al., 2023b). However, the judgment of the nonlinear relationship is not consistent, "U shape", "inverted U shape" and "J shape" have all been seen in the literature (Wang and Shen, 2016).

From the literature, it is found that, first, most of the research objects are enterprises or industries, and there are few researches based on macro data. There are many administrative divisions in China, and the environmental regulations of each city are different. The use of city level macro-data can help us to explore this issue more deeply, and also provide useful reference for the government's environmental governance. Then, whether the conclusion is still non-linear when we use China's urban data? Is environmental regulation an effective tool to promote China's green development in city level? As far as we know, the previous literature has not made a full discussion for above-mentioned problems. In addition, researchers usually chose different periods, which may also lead to inconsistent judgment of nonlinear forms. In 2012, the 18th National Congress of the Communist Party of China emphasized the construction of ecological civilization in a prominent position, and China's environmental regulation laws and regulations system has entered a deepening stage. Since then, there has been no formal discussion in the literature on the evolving trends of green development and whether environmental regulation can promote green development.

2.2 Environmental regulation, technological innovation and green development

Scholars have found that technological innovation, energy efficiency and human capital may be the causes of the non-linear effects of environmental regulations on green development. Among them, technological innovation factors are mostly discussed.

In terms of empirical research, most of them focus on the impact of environmental regulation on technological innovation and technological innovation on green development. There are few studies on the relationship between all of them. Although some literature find that technological innovation affects the green development effect of environmental regulation (Zhan et al., 2023), few studies find the role form of technological innovation. Scholars agree that the improvement of innovation level has a positive impact on green development (Ouyang et al., 2020; Ren et al., 2023a). There are two possible mechanisms. The first mechanism, the innovation of production process can improve the efficiency of resource utilization, and the innovation of production products can meet the higher demand of consumers, improve the diversity of products, expand the market power of enterprises, and thus increase the profit margin of enterprises. Follow this path, then it improves the economic efficiency of the region. The second mechanism, the innovation of enterprise production process and production technology can improve the utilization rate of traditional fossil energy, thereby reducing the pollution emissions of enterprises and improving the regional environmental quality. At the same time, enterprises produce more environmental protection technology products through technological innovation, which can accelerate the development of environmental protection industry in the long term, and thus enhance the green development of the region. Scholars have different conclusions on the direction of technological innovation effect of environmental regulation (Shi et al., 2018; Hu et al., 2020), which may be the cause of the non-linear impact of environmental regulation on green development.

In terms of theoretical research, scholars build theoretical models to explore how environmental factors affect economic growth. Some researchers incorporated pollution into the consumer utility function, or built a neoclassical growth model including environmental pollution, then analyzed the dynamic relationship between environmental pollution and economic development (Selden and Song, 1995). Some researchers embed pollution into, but its optimal growth path is more complicated (Stiglitz, 1974). Another group of scholars incorporate environmental pollution into the endogenous growth model to explore the impact of resource depletion, environmental quality, and government policies on sustainable development. Some scholars also try to identify the impact of environmental protection or its specific policies (such as carbon emission reduction policies) on economic growth by using various dynamic equilibrium models, such as the overlapping generation model OLG, the computable general equilibrium model and dynamic stochastic general equilibrium model DSGE (Jiang et al., 2022b).

It can be found that, previous literature pay attention to the direct economic and environmental effects of environmental regulation, and attaches importance to the impact of both environmental regulation on technological progress and technological progress on green development, but there are few discussions on incorporating those into an integrated research framework. Even if the study involved the relationship among the three, it did not involve green development. Meanwhile, scholars have focused on the role of technological innovation in the impact of environmental regulation on green development, but few have discussed its role form. Therefore, how technological innovation plays a role in the impact of environmental regulation on green development and whether it is moderated by other factors need to be further studied. Finally, in theoretical analysis, previous literature only discussed the impact of environmental regulation on economic growth or sustainable development, and did not include technological innovation. And environmental pollution is only incorporated into the production function and utility function, and does not involve the whole process. In the long run, the solution to environmental pollution depends on technological progress (Brock and Taylor, 2010), and environmental regulations will have an impact on green development in every process of enterprise production. Therefore, it is urgent to systematically analyze the theoretical mechanism of environmental regulation, technological innovation and green development.

2.3 Measurement of environmental regulation

For the measurement of environmental regulations, qualitative description was used in the early stage, but it was difficult to reflect regional differences and time changes, so more scholars turned to a single quantitative indicator (Wang et al., 2022). It can be divided into two types: input type indicator and performance type indicator. The former measures the direct cost of compliance with environmental regulations and the cost paid by the government and environmental protection agencies to implement regulations and ensure the effect of regulations. For example, pollution reduction cost (regulatory compliance cost), sewage fee (tax), environmental pollution treatment investment, and industrial pollution treatment investment completed (Cole and Robert, 2003), etc. The latter reflects the pollution level of enterprises under government environmental regulations and reflects the performance of government environmental regulations. For example, the regional distribution of polluting enterprises, the number of environmental litigation cases, the number of supervision and inspection, and the discharge of major pollutants (Xepapadeas and de Zeeuw, 1999). Environmental regulation contains many contents, which cannot be completely summarized by a single quantitative indicator, so scholars generally turn to the comprehensive index. In terms of indicator selection, in order to study the effect of environmental regulation, performance-based indicators are particularly popular. While taking the comparability of each single indicator into account, the most common is the use of major pollutant emissions. Some researchers like to construct a comprehensive environmental regulation index based on the discharge of "three wastes", "five wastes" and the pollutant removal rate (Song et al., 2022; Xu et al., 2022).

In terms of the classification of environmental regulations, according to the nature of the subject, most scholars divide environmental regulations into three types: command-and-control type, market-incentive type and public participation type (Chen et al., 2021). Therefore, it is necessary to explore the difference in green development effects of different environmental regulations. Some scholars used the differential method to evaluate the effect of specific policies. For example, they found that the implementation of the Air Pollution Control Action Plan would inhibit the efficiency of green development (Zhan et al., 2023). It can be found that the classification of environmental regulations by pollutants and periods is not common. So, the impact of environmental regulations of different periods and different pollutants on green development has not yet been fully studied.

In view of this, we try to make some improvements in this field. Firstly, we integrate environmental regulation, technological innovation and green development into a unified research framework. Based on Chinese city-level data, we explore the green development effects of environmental regulations and the differences in the green development effects of environmental regulations for cities with different geographical locations, urban agglomerations, city sizes and pollution levels. At the same time, we explore the mediation effect of technological innovation in environmental regulation affecting green development, the moderating effect of industrial structure, and the threshold role of technological innovation in environmental regulation affecting green development.

Secondly, we enrich the theoretical basis of environmental regulation, technological innovation and green development. A theoretical model including environmental regulation, technological innovation and green output is constructed to analyze the intermediate role and form of technological innovation in the impact of environmental regulation on green development.

Finally, we construct appropriate environmental regulation indicators to investigate the impact of different types of environmental regulation on green development. We use the emission of major pollutants to construct a comprehensive index of environmental regulation, and divide environmental regulation into early emission reduction type and late treatment type according to the period, and sulfur dioxide environmental regulation and smoke (powder) dust environmental regulation according to the pollutant. Then we explore the difference of effects of different types of environmental regulations on green development, and compare the difference of threshold effects of technological innovation on different types of environmental regulations on green development.

3 Theory and mechanism

Referring to the theoretical framework of environmental regulation affecting technological innovation (Acemoglu et al., 2012), this paper constructs a theoretical model including environmental regulation, technological innovation and economic output.

Suppose a country includes two regions a and b. The two regions rely on capital and labor factors to produce products, products and factors can flow freely. The economic output of the final product adopts the CES production function:

$$Y = \left(\sum_{j \in [a,b]} Y_j^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}} \tag{1}$$

Where, Y_j represents the economic output of the region j, $j \in [a, b]$. ε represents the substitution elasticity between products of a and b.

Production function and pollution function of the region j:

$$Y_j = L_j^{1-\alpha} \int_0^1 A_{ji}^{1-\alpha} k_{ji}^{\alpha} di \tag{2}$$

$$e(Y_j) = [1 - \theta(A_j)] L_j^{1-\alpha} \int_0^1 A_{ji}^{1-\alpha} k_{ji}^{\alpha} di \tag{3}$$

Where, L_j represents the labor input of j. A_j represents the technical level of j. A_j is the quality of the capital goods i used by the region j. k_{ji} is the quantity of the i capital goods used by the region j. α is the elasticity of capital output. $e(Y_j)$ is pollution output. $\theta(A_j)$ is technological innovation and emission reduction capacity.

The profit maximization decision of region j is:

$$\max_{[L_j, k_{ji}]} P_j Y_j - W_j L_j - \int_0^1 p_{ki}^j k_{ji} di - \tau_j P_j e(Y_j) \tag{4}$$

Among them, P_j、 W_j、 p_{ki} are output, labor and capital prices. τ_j is environmental regulation, expressed by pollution tax rate. Find the first-order condition of profit maximization for formula (4), solve the capital price and labor price.

Assuming that capital goods are produced by monopoly manufacturers, the production cost and use price are $\alpha^2 r_j$ and p_{ki}^j. The optimal output of capital goods $\max(p_{ki}^j k_{ji} - \alpha^2 r_j k_{ji})$ can be obtained from the profit maximization decision $k_{ji}^{'}$ Substitution formula (2) solves the regional optimal output.

$$Y_j = r_j^{\frac{\alpha}{\alpha-1}} P_j^{\frac{\alpha}{1-\alpha}} \left[1 - \tau_j\left(1 - \theta(A_j)\right)\right]^{\frac{\alpha}{1-\alpha}} L_j A_j \tag{5}$$

Derivation of environmental regulation τ_j with optimal output Y_j

$$\frac{\partial Y_j}{\partial \tau_j} = r_j^{\frac{\alpha}{\alpha-1}} P_j^{\frac{\alpha}{1-\alpha}} \left[1 - \tau_j\left(1 - \theta(A_j)\right)\right]^{\frac{\alpha}{1-\alpha}} L_j \left\{ \frac{\partial A_j}{\partial \tau_j} + \frac{A_j}{1 - \tau_j\left(1 - \theta(A_j)\right)} \left(\theta(A_j) + \tau_j \frac{\partial \theta(A_j)}{\partial \tau_j} - 1 \right) \right\} \tag{6}$$

For simplicity, let $M = \partial A_j / \partial \tau_j$, and $\Phi = \frac{A_j}{1-\tau_j(1-\theta(A_j))} (\theta(A_j) + \tau_j \frac{\partial \theta(A_j)}{\partial \tau_j} - 1)$. Under normal conditions, Φ is less than 0. Given $\Phi < 0$, if environmental regulations suppress technological innovation ($M < 0$), environmental regulations inevitably suppress economic output ($\partial Y_j / \partial \tau_j < 0$). When $M > 0$, environmental regulations promote technological innovation, then the direction of the impact of environmental regulations on economic output depends on the absolute value of M and Φ. If $M < |\Phi|$, then $\partial Y_j / \partial \tau_j < 0$, environmental regulations suppress regional economic output; if $M > |\Phi|$, then $\partial Y_j / \partial \tau_j > 0$, environmental regulations promote regional economic output.

According to the above theoretical discussion, two hypotheses are proposed.

H1: The impact of environmental regulations on regional economic output is non-linear, and its mode varies with the type of environmental regulation and the type of cities.

H2: Technological innovation is a key factor that restricts the impact of environmental regulations on green output; besides mediating effect, it also has an important moderating effect.

4 Variables and data

This paper aims to study the impact of environmental regulation on urban green development in China through technological innovation. Therefore, this study used data from 286 cities in China mainland from 2003–2019 (a few cities were excluded from the analysis due to lack of data).

4.1 Dependent variable

The dependent variable is Green Total Factor Productivity (GTFP), which is represented by green total factor productivity. Currently, there are two main methods of measuring GTFP: traditional radial and angular DEA models (including DEA-CCR and DEA-BCC) and non-radial, non-angular SBM-DEA models. The radial and angular DEA models assume that output and input increase in proportion, it do not account for non-desirable outputs, such as pollution emissions. This can lead to biases in the measurement of GTFP. To overcome these limitations, this paper uses the SBM-DEA model for measuring GTFP. Additionally, the GML productivity index is used to represent GTFP in this study.

For the measurement of the GTFP, two types of input factors (labor and capital) and two types of output (desirable and non-desirable) are considered. The specific indicators selected are as follows: (1) labor input:

number of employed persons in each city; (2) capital input: stock of fixed assets; (3) desirable output: GDP of each region; (4) there are significant differences among scholars in the selection of non-desirable output indicators, mainly focusing on industrial pollution emissions, including industrial three wastes (Ji et al., 2022), industrial SO2 and COD (Zhong et al., 2022), carbon dioxide (Luo et al., 2022) and industrial SO2 (Watanabe and Tanaka, 2007). Since the "new normal," the share of China's industrial economy in the national economy has continuously decreased. Achieving carbon peak and carbon neutrality has become the main goal of environmental governance, and air pollution prevention and control also requires key breakthroughs. Therefore, this paper selects carbon emissions and PM2.5 concentration, while examining the dual non-desirable constraints of climate change and environmental pollution accompanying economic development. The PM2.5 meteorological grid data is obtained from Dalhousie University. To obtain the PM2.5 at the municipal level in China from 2003 to 2019, GIS overlay analysis tools are used and summarized by mean classification. Carbon emission data comes from the CEADs database. Other data are from the "China City Statistical Yearbook" from 2004 to 2020.

4.2 Core Explanatory Variables

(1) Environmental regulation (ER). Environmental regulation covers a wide range of content and cannot be fully captured by a single quantitative indicator. Scholars mainly construct a comprehensive index of environmental regulation intensity based on "three wastes" emissions (Song et al., 2022), while others use five pollution indicators of industrial wastewater, SO2, smoke, dust, and solid waste (Xu et al., 2022), or pollution removal rate indicators for synthesis (Zhou et al., 2017). However, the measurement method of environmental regulation still faces severe data constraints and needs to explore new, obtainable and widely recognized indicators by scholars."

In this study, the environmental regulation index is synthesized using "three wastes" emissions and removal indicators. Since industrial wastewater emissions data are no longer publicly available after 2010, only two pollution indicators, industrial sulfur dioxide and industrial smoke (dust), are used. The environmental regulation index is synthesized using the entropy weight method based on four indicators: industrial sulfur dioxide emissions, industrial sulfur dioxide removal, industrial smoke (dust) emissions, and industrial smoke (dust) removal.

Environmental regulation is classified into two types based on the period: early-stage emission reduction-type (ER1) and later-stage governance-type (ER2). ER1 is derived from the weighted average of the emissions of two pollutants, industrial sulfur dioxide and industrial smoke (dust), while ER2 is derived from the weighted average of the removal of two pollutants. Based on pollutants, it is further classified into sulfur dioxide environmental regulation (ER3) and smoke (dust) environmental regulation (ER4). ER3 is derived from the weighted average of industrial sulfur dioxide emissions and removal, while ER4 is derived from the weighted average of industrial smoke (dust) emissions and removal. All this data come from the "China City Statistical Yearbook".

(2) Technological innovation (TI). Following the methodology of Yang and Wang. (2022), the ratio of patent applications to employment is employed to measure the technological innovation generated by human capital in a region. Additionally; Acemoglu et al. (2012) propose that, in the long run, green technological innovation is more favorable for creating a better environment. Moreover, environmental regulations that promote technological innovation will directly result in the emergence of green technology. Therefore, this paper also utilizes green technological innovation (GTI) as a model variable, which can not only provide a robustness check for the empirical findings in subsequent sections but also more precisely portray the central role of technological innovation in the green development impact of environmental regulation. Green technological innovation is represented by the ratio of green patent applications to employment. Patent data is sourced from the China Patent Publication Gazette.

4.3 Control variables

To address endogeneity caused by omitted variables, we selected several control variables including regional openness (fdi), government intervention (gov), infrastructure level (cov), and informatization level (int). Data are from the "China City Statistical Yearbook". The composition and descriptive statistics of these indicators are provided in Table 1.

The results show that the mean of the green development growth rate is greater than 1. Its variability is relatively large based on the sample range and standard deviation. This suggests that the green development of Chinese prefecture-level cities is constantly improving but has a greater variability. Additionally, the minimum value of the green development growth rate is less than 1, indicating that some regions still face severe environmental pollution or weak government environmental governance, resulting in low levels of green development. Furthermore, the standard deviation of environmental regulation and its classification indicators is large due to differences in resource endowments and environmental conditions among Chinese prefecture-level cities. As a result, the intensity of environmental regulation implemented by the government also varies in different years. Finally, the mean of technological innovation is small, and some regions have no innovation output, which suggests that China's technological innovation capability is weak. The government needs to increase investment in technological innovation and formulate relevant policies to encourage enterprises to innovate.

5 Analysis of empirical results

5.1 Impact of environmental regulations on green development

5.1.1 Basic analysis

To assess the effectiveness of environmental regulation on green development, this paper constructs a fixed-effect model to analyze the direct impact. Additionally, it compares the differences in the direct impact of early emission reduction environmental regulation and later governance-oriented environmental regulation, as well as sulfur dioxide environmental regulation and smoke (dust) environmental regulation on green development.

$$GTFP_{it} = \alpha_1 + \beta_1 X_{it} + \phi_1 q X_{it} + \gamma_1 W_{it} + \sigma_{1i} + \tau_{1t} + \varepsilon_{1it} \quad (7)$$

TABLE 1 Statistical descriptions of variables.

Variable	Code	Definition	Mean	Standard Deviation	Minimum	Maximum
Dependent Variable	GTFP	Green total factor productivity	1.001	0.021	0.779	1.143
Core Explanatory Variables	ER	Environmental regulation index	0.502	0.014	0.258	0.743
	TI	Number of patent applications/Employment (pcs/ten thousand person)	0.295	1.178	0.021	21.198
	GTI	Number of green patent applications/Number of employees (pcs/ten thousand person)	0.175	0.249	0.004	3.699
	ER1	Emission reduction environmental regulation index	43.294	41.072	0.986	271.325
	ER2	Governance environmental regulation index	838.833	974.844	1.182	4981.087
	ER3	Sulfur dioxide environmental regulation index	80.303	103.439	0.804	637.242
	ER4	Smoke (powder) dust environmental regulation index	800.252	940.429	2.414	4820.496
	So2	Industrial sulfur dioxide emissions (ten thousand tons)	57.890	57.801	0.718	341.27
	So2w	Industrial sulfur dioxide removal capacity (ten thousand tons)	98.275	161.521	0.310	962.388
	smok	Industrial smoke (powder) dust emission (ten thousand tons)	26.768	27.735	0.592	166.142
	smokw	Industrial smoke (powder) dust removal capacity (ten thousand tons)	157.038	186.752	0.968	959.843
Control Variables	fdi	Foreign direct investment/GDP (%)	28.610	27.170	0.098	95.856
	gov	Government expenditure/GDP (%)	18.367	14.659	3.128	101.277
	cov	Bus ownership/total population (vehicles/ten thousand person)	3.064	4.451	0.079	82.320
	tec	Internet users/total population (%)	13.879	14.810	0.006	84.252

Data sources:Carbon emission data comes from the CEADs, database. Patent data is sourced from the China Patent Publication Gazette. additionally, Other data sources are both from the "China City Statistical Yearbook".

TABLE 2 Green development effects of environmental regulation and its classification policies.

Parameters	Group 1	Group 2				Group 3			
	ER	ER1	ER2	ER3	ER4	so2	so2w	smok	Smokw
β_1	−0.060* (0.036)	−0.011 (0.012)	−0.065* (0.039)	−0.028 (0.029)	−0.111** (0.054)	−0.00004*** (0.00001)	−5.33e-6 (5.45e-6)	−0.0002* (0.0001)	−7.35e-7** (3.57e-7)
ϕ_1	0.057* (0.029)	0.055 (0.029)	0.059** (0.029)	0.133 (0.087)	0.051** (0.023)	2.57e-8** (1.1e-8)	5.07e-9 (3.26e-9)	3.90e-9** (1.82e-9)	2.29e-12** (1.04e-12)

The estimated result is obtained by Stata16.0; the robust standard errors are in parentheses; *, **, *** indicates significance at the levels of 10%, 5%, and 1%, the same below.

Here, $GTFP_{it}$ represents the green development of region i in year t, X_{it} represents the environmental regulation of region i in year t, qX_{it} is the quadratic term of environmental regulation, including ER, $ER1$, $ER2$, $ER3$, $ER4$, $so2$, $so2w$, $smok$, $smokw$, while control variables include W_{it}, σ_i and τ_t represent individual fixed effects and time fixed effects, β and ϕ are the primary parameters to be estimated.

Table 2 presents the results of the green development effects of environmental regulation and its classified policies. Firstly, the impact of environmental regulation on green development follows a U shaped. Low-intensity environmental regulation inhibits green development due to the "cost-effect" until a certain threshold is crossed, which then drives innovation and promotes green development in the region. Secondly, when examining early and later stages separately, the effect of early emission reduction environmental regulation is not significant, but the later governance-oriented environmental regulation has a clear U shaped effect on green development. Thirdly, looking at different pollutants, only the regulation of sulfur dioxide has no significant effect on promoting green development. This is because the early control of sulfur dioxide was effective, but the fast-acting later treatment had no effect. Smoke (dust) environmental regulation has a clear U shaped effect, and both early and later environmental regulations are effective, with stronger early effects. Compared to smoke (dust), the conversion technology of sulfur dioxide is complex and difficult to recycle, leading to differences in the

TABLE 3 Impacts of environmental regulation, technological innovation and green development (replacement of core explanatory variables).

Parameters	ER
β_1	−0.072* (0.044)
ϕ_1	0.074** (0.037)

effects of environmental regulation on the two pollutants. Clean standards should be developed according to the characteristics of the two pollutants, and research and development investment should be increased to promote the development of green technology for smoke (dust). In summary, the intensity of environmental regulation in various regions can only promote green development if it exceeds a certain threshold. Hypothesis 1 (H1) is strongly verified.

5.1.2 Robustness test

After the conclusion is reached, we need to test the robustness of the conclusion to verify whether it is reliable (Ren et al., 2023c). The function of the robustness test is to avoid the chance of accidental results. It is common practice to replace the important variables (explained and explanatory) by those with the same economic implications and re-run the regression. In order to verify the robustness of above results, this paper changes the explanatory variables and the explained variables, and conducts regression again.

(1) Replacement of core explanatory variable. In previous articles, the environmental regulation index was synthesized using the emission and treatment amount of sulfur dioxide and smoke (powder) dust as explanatory variables. Here, we add the emission and treatment amount of other pollutants to synthesize a new environmental regulation index as an explanatory variable in the robustness test. Including industrial wastewater discharge, industrial sulfur dioxide discharge, industrial smoke (powder) dust discharge, sewage treatment rate, harmless treatment of domestic waste, comprehensive utilization rate of industrial solid waste, industrial sulfur dioxide removal, industrial smoke (powder) dust removal. Furthermore, Eq 7 is re-estimated, and the results are shown in Table 3.

The results show that the estimated value have the same direction and similar size compared with the previous estimates, indicating that the results obtained above are quite robust. In addition, we can also find a useful conclusion that the more indicators to construct environmental regulation, the more extensive the aspects covered by environmental regulation, the more obvious its effect on green development.

(2) Substitute the dependent variable. In the previous article, we used carbon emissions and PM2.5 to represent the undesirable output, and then measured green total factor productivity as explained variables. In recent years, under the theme of carbon peak and carbon neutrality, China has introduced many regulatory policies on carbon emissions. Therefore, using carbon emissions to represent the undesirable output, the calculated green total factor productivity can more accurately describe the green development level under the carbon emission regulation policy. Therefore, in the calculation of green total factor productivity as the dependent variable, only carbon emissions is used for the non-expected output in the robustness test.

Once again, Eq 7 is re-estimated, and the regression results are shown in Table 4. There is little difference compared with previous results, indicating that our results are robust. In addition, when the pollution output only considers carbon emissions, the green development effect of environmental regulation is weakened, but the change is not large. China needs the long-term persistence and efforts of the government in order to achieve the goal of CO_2 emission peak and carbon neutrality targets, and promote the green and low-carbon development (Zhao et al., 2022).

5.1.3 Heterogeneity analysis

Under different conditions, the influence of variables is heterogeneous (Zheng et al., 2022). According to geographical location, 286 cities we used are divided into four regions: East, Central, West and Northeast. According to their city clusters, they are divided into ten key city clusters (select the representative Beijing-Tianjin-Hebei, Guangdong-Hong Kong-Macao, Yangtze River Delta, the middle reaches of the Yangtze River, Chengdu-Chongqing five key city clusters). According to the population size in 2019, they are divided into five types[3]: small city, medium-sized city, large city, supercity and megacity. According to the four points of the pollution level in 2019, they were divided into four types[4]: ultra-heavy pollution, heavy pollution, moderate pollution and lightly polluted cities. Re-estimation Eq 7 compares the impact of urban environmental regulations on green development under different classification criteria.

The results of geographical location heterogeneity analysis are shown in Table 5. In central and northeast China, environmental regulations are ineffective for green development. The influence of environmental regulation on green development in western China is positive. The green development effect of environmental regulation in eastern China shows an inverted U shape. The eastern region has greater effect than the western region. Western China is the heavy chemical industry base, the excessive development of mineral resources has caused serious environmental pollution, but subject to the lack of innovation and less foreign investment, the direct effect is not the strongest compared with other regions. In eastern China, the economic development level is higher, the infrastructure is better, the industrial scale and innovation potential is larger, the industrial structure is more reasonable, and the environmental protection system is relatively complete, so the environmental regulation has a strong promoting effect on green development. The above findings confirm hypothesis H1 again.

3 According to the number of permanent residents in urban areas, less than 0.5 million is a small city, 0.5 to 1 million is a medium-sized city, 1 to 5 million is a large city, 5 to 10 million is a supercity, and more than 10 million is a megacity.

4 The degree of pollution is expressed by the entropy weight of the emissions of industrial "three wastes" in 2019.

TABLE 4 Green development effects of environmental regulation and its classification policies (replacement of dependent variable).

Parameters	Group 1	Group 2				Group 3			
	ER	ER1	ER2	ER3	ER4	so2	so2w	smok	Smokw
β_1	−0.046* (0.023)	−0.049 (0.010)	−0.041** (0.020)	−0.007 (0.010)	−0.113** (0.057)	−0.00001** (6.37e-6)	−5.20e-6 (4.07e-6)	−0.0002* (0.0001)	−3.32e-7** (1.38e-7)
ϕ_1	0.031* (0.017)	0.011 (0.027)	0.023* (0.012)	0.366 (0.528)	0.020** (0.010)	3.96e-9 (4.85e-9)	2.91e-10 (2.49e-10)	4.46e-9 (3.32e-9)	5.20e-12** (2.17e-12)

TABLE 5 Geographical location heterogeneity (four regions).

Variable	East	Central	West	Northeast
ER	0.024** (0.011)	0.005 (0.012)	0.017*** (0.006)	0.007 (0.013)
qER	−0.016*** (0.006)	0.009 (0.013)	0.012*** (0.004)	0.005 (0.024)

TABLE 6 Heterogeneity of urban agglomeration (five major urban agglomeration).

Variable	Beijing-Tianjin-Hebei city region	Guangdong-Hong Kong-Macao Greater Bay Area	The Yangtze River Delta	The Middle reaches of the Yangtze River	Chengdu-Chongqing city group
ER	0.058*** (0.017)	0.044*** (0.014)	0.014*** (0.002)	−0.049*** (0.014)	−0.127* (0.067)
qER	−0.025 (0.045)	−0.039* (0.021)	−0.015* (0.008)	0.039* (0.022)	0.114** (0.057)

TABLE 7 Urban size heterogeneity.

Variable	Small city	Medium-sized city	Large city	Supercity	Megacity
ER	−0.006 (0.021)	0.068*** (0.024)	0.130* (0.075)	0.149*** (0.019)	−0.503*** (0.176)
qER	0.008 (0.011)	−0.030 (0.019)	−0.074** (0.032)	−0.018*** (0.005)	0.426*** (0.130)

The results of urban agglomeration heterogeneity are shown in Table 6. Environmental regulation can promote green development in the Beijing-Tianjin-Hebei region, the Guangdong-Hong Kong-Macao Greater Bay Area and the Yangtze River Delta, and has a U shaped impact on the middle reaches of the Yangtze River and Chengdu-Chongqing city group. The Guangdong-Hong Kong-Macao Greater Bay Area and the Yangtze River Delta have leading innovative technologies and reasonable industrial structures, but the impact of the Guangdong-Hong Kong-Macao Greater Bay Area is greater than that of the Yangtze River Delta. The Yangtze River Delta includes cities in Anhui Province with relatively slow development, which have relatively insufficient technological innovation power and relatively small industrial scale, so the response ability of green development to environmental regulations is relatively slow. In the western and central urban agglomerations, the "innovation compensation effect" of environmental regulation has not yet appeared. The government needs to strengthen environmental regulation. In particular, those cities should vigorously develop emerging technology industries and service industries, research and develop clean technologies and low-carbon environmental protection processes, reduce resource and energy consumption, and improve innovation efficiency, so as to improve environmental quality and green development. The results are highly consistent with H1.

The estimated results of urban size heterogeneity are shown in Table 7. The environmental regulation in megacity has a U shaped impact on green development, the supercity and large city have an inverted U shaped impact, the effect of medium-sized cities is positive, and the effect of small cities is not significant. Megacity has large population size, high human capital level and great innovation potential. After the "cost scale" effect, the increase of environmental regulation can significantly improve green development through technological innovation. The innovation base of supercity and large city is not sufficient to support the positive effect of excessive environmental regulations. Medium-sized cities and small cities need to strengthen environmental regulations. By comparing the effects of environmental regulations of different urban scales, it is found that with the increase of urban scale, the promoting effect of environmental regulations on green development gradually appears and increases until the excessive inhibitory effect disappears. The above findings still strongly support H1.

TABLE 8 Heterogeneity of urban pollution degree.

Variable	Ultra-heavy polluted cities	Heavy polluted cities	Moderate polluted cities	Light polluted cities
ER	0.215*** (0.075)	0.186*** (0.013)	0.124*** (0.041)	0.003 (0.007)
qER	0.007 (0.009)	−0.067** (0.030)	−0.146*** (0.055)	−0.004 (0.003)

The heterogeneity analysis results of cities with different pollution levels are shown in Table 8. Increasing environmental regulations in ultra-heavily polluted cities plays an obvious role in promoting green development. Increasing environmental regulations in heavily and moderately polluted cities will promote green development, but excessive environmental regulations will inhibit it. The effect of environmental regulation on lightly polluted cities is weak and not statistically significant. By comparing the effects of urban environmental regulations with different pollution levels, it is found that with the deepening of urban pollution levels, the promoting effect of environmental regulations on green development gradually appears and increases until the excessive inhibitory effect disappears. The results are still consistent with H1.

TABLE 9 Test of the mediating effect of technological innovation.

Parameters	TI	GTI
Global Treatment Effects β_2	0.128*** (0.031)	0.132*** (0.034)
β_3	0.267***	0.183***
	(0.063)	(0.025)
φ_4	0.367** (0.183)	0.596** (0.239)
Direct Effect β_4	0.124***	0.129***
	(0.033)	(0.037)
Indirect Effect $\beta_3{}^*\varphi_4$	0.098***	0.109***

For Eqs 8–10, the fixed effect model is used to estimate.

5.2 Impact of environmental regulation and technological innovation on green development

5.2.1 Mediated effect test with adjustment

To shed light on the causes of nonlinear effect of environmental regulation on green development, this paper regards technological innovation and green technological innovation as mediating variables, uses the mediated effects model (Muller et al., 2005) to verify their mediating roles, clarify the specific mechanisms and their strengths. At the same time, industrial structure (IND) is regarded as a moderating variable to analyze whether the mediated effect of technological innovation is regulated by IND.

Firstly, we test the overall processing effect of environmental regulation on green development, without introducing the mediating variables into the model. Eq. 8 is constructed for this purpose.

$$GTFP_{it} = \alpha_2 + \beta_2 ER_{it} + \gamma_2 W_{it} + \sigma_{2i} + \tau_{2t} + \varepsilon_{2it} \tag{8}$$

Secondly, taking technological innovation (and green technological innovation) as the dependent variable and environmental regulation as the independent variable, Eq. 9 is constructed for explanation using the mediating variables.

$$M_{it} = \alpha_3 + \beta_3 ER_{it} + \gamma_3 W_{it} + \sigma_{3i} + \tau_{3t} + \varepsilon_{3it} \tag{9}$$

Here, M_{it} represents the mediating variable, which includes technological innovation TI_{it} and green technological innovation GTI_{it}.

Finally, both environmental regulation and technological innovation are used as independent variables to test the mechanism by which environmental regulation affects green development through technological innovation. At the same time, the cross-multiplication term of technological innovation and industrial structure is added to explore whether the mediation effect of technological innovation is moderated by industrial structure. Eq. 10 is constructed for this purpose.

$$GTFP_{it} = \alpha_4 + \beta_4 ER_{it} + \varphi_4 M_{it} + \theta_4 M_{it}{}^*IND_{it} + \gamma_4 W_{it} + \sigma_{4i} + \tau_{4t} + \varepsilon_{4it} \tag{10}$$

Table 9 presents the estimation results. (1) The direct effect β_4 and indirect effect $\beta_3{}^*\varphi_4$ of both technological innovation and green technological innovation are significant. They both have positive mediating effects. Environmental regulation can promote green development through technological innovation and green technological innovation, verifying hypothesis H2. (2) The direct and indirect effects of green technological innovation are stronger than those of technological innovation. Green technological innovation is relatively cleaner and more efficient, resulting in a stronger promotion of green development. (3) Regardless of whether the mediating variable is technological innovation or green technological innovation, the results of both models show that the direct effect is greater than the indirect effect. The impact of environmental regulation on green development is mainly direct, and the intermediary role of technological innovation is secondary. This cannot explain the nonlinear effect of environmental regulation on green development. (4) The interaction item of industrial structure and technological innovation is significantly positive at the 1% level, reflecting that industrial structure has a moderated effect on the mediating effect of technological innovation, and environmental regulation can significantly improve green development through the interaction item. (5) Comparing the moderated effects of industrial structure for technological innovation and green technology innovation respectively, industrial structure and green technology innovation are greater, indicating that environmental regulation is more likely to significantly improve green development through the interaction item.

TABLE 10 Threshold effect test (BS number = 500).

Variable	Threshold number	F Value	*p*-Value	10% critical value	5%critical value	1%critical value
ER	Single threshold	10.790*	0.098	10.678	12.567	18.537
	Double threshold	8.450	0.170	11.762	16.234	22.744
ER1	Single threshold	16.992**	0.014	11.562	13.780	17.693
	Double threshold	13.234**	0.032	9.037	10.784	15.609
	Triple threshold	4.461	0.756	16.829	20.172	27.615
ER2	Single threshold	10.807*	0.086	9.837	13.274	18.307
	Double threshold	8.442	0.202	13.017	16.036	21.081
ER3	Single threshold	12.026*	0.074	10.725	13.004	17.694
	Double threshold	6.614	0.306	10.957	14.397	21.160
ER4	Single threshold	11.358**	0.028	8.080	9.505	16.392
	Double threshold	7.123	0.196	9.024	11.281	15.997

TABLE 11 Threshold regression results.

Variable	Estimates	T Value	*p*-Value
$ER \cdot I(TI \le 0.010)$	−0.008*	−1.661	0.098
$ER \cdot I(TI > 0.010)$	0.444**	1.987	0.048
$ER1 \cdot I(TI \le 0.008)$	−0.340	−0.853	0.398
$ER1 \cdot I(0.008 < TI \le 0.014)$	−0.802**	−2.043	0.042
$ER1 \cdot I(TI > 0.014)$	−0.682*	−1.862	0.064
$ER2 \cdot I(TI \le 0.009)$	−0.017*	1.977	0.050
$ER2 \cdot I(TI > 0.009)$	0.443**	−2.116	0.036
$ER3 \cdot I(TI \le 0.012)$	−0.007	2.156	0.232
$ER3 \cdot I(TI > 0.012)$	0.167***	−2.974	0.003
$ER4 \cdot I(TI \le 0.216)$	−0.042*	1.898	0.060
$ER4 \cdot I(TI > 0.216)$	0.867**	−2.333	0.020

5.2.2 Threshold effect test

The basic analysis results indicate that environmental regulations only promote green development beyond a certain threshold. The results of the mediation analysis show that environmental regulations promote technological innovation. Additionally, technological innovation will inevitably promote green development. Combining these three factors, we can analyze the threshold effect of technological innovation and reveal the nonlinear impact of environmental regulation on green development. Therefore, taking technological innovation as the threshold variable and using the panel threshold effect model (Hansen, 1999), we can identify the conditions under which technological innovation has positive effect of environmental regulations and accelerate the promotion of green development. The model is as follows:

$$GTFP_{it} = \alpha_5 + \delta_1 ER_{it} \bullet I(TI_{it} \le \eta) + \delta_2 ER_{it} \bullet I(TI_{it} > \eta) + \gamma_5 W_{it} + \sigma_{5i} + \tau_{5t} + \varepsilon_{5it} \quad (11)$$

Here, TI_{it} represents the level of technological innovation in region i at time t, where I is an indicative variable, η is the threshold value, δ is the main parameter to be estimated.

Firstly, the number and values of thresholds are determined. Table 10 shows that at a significant level of 10%, the environmental regulation has a significant F-value for a single threshold, indicating the presence of a single threshold effect.

Secondly, we employed a panel threshold model with single threshold. The results are presented in Table 11, which indicating that: (1) when technological innovation (measured by patent applications per 10,000 employed persons) is less than 0.01, a unit increase in environmental regulation leads to a reduction of 0.008 units in green development. Thus, at low levels of technological innovation, it is not conducive to improving green development; (2) when technological innovation is greater than 0.01, a unit increase in environmental regulation results in an increase of 0.444 units in green development. Once technological innovation surpasses the threshold, environmental regulation stimulates the green creativity of enterprises, promotes green development. Moreover, it compels high-energy-consuming enterprises to withdraw from the market. The remaining enterprises choose to enhance their core competitiveness through technological innovation. The industry's overall technological innovation displays an upward spiral trend. Over time, this enhances the region's green total factor productivity, thereby fostering regional development. These empirical results, on the one hand, confirm hypothesis H2, and explain the cause of the nonlinear impact of environmental regulations on green development, on the other hand.

The results of the classification policy indicate that: (1) Technological innovation has a dual threshold effect in early emission reduction environmental regulation, but only a single threshold effect in sulfur dioxide environmental regulation. However, regardless of the level of technological innovation, neither of these regulations can promote green development, which is consistent with the basic analysis conclusion. (2) Technological innovation has a single threshold in later governance-oriented environmental regulation and smoke (dust) environmental regulation, with threshold values of 0.012 and 0.216. The threshold effect results are consistent with the previous findings: the threshold values change from inhibition to promotion. When technological innovation exceeds 0.012 and 0.216, there is sufficient technological support for these regulations, which can promote regional green development.

6 Discussion

With the data of Chinese cities from 2003 to 2019, the empirical analysis finds that the impact of environmental regulations on green development is U shaped. Low intensity environmental regulations follow the "cost effect" and inhibit green development. Only when environmental regulations go beyond a certain level will green development be promoted. The hypothesis H1 is strongly verified. According to the calculation, the U shaped turning point is 0.39, and the mean environmental regulation intensity (0.502) is on the right side of the turning point. It shows that environmental regulation promotes green development after China enters into the initial stage of high-quality development and environmental regulation policy. The data period used in this paper is similar to Feng and Chen (2018), Shang et al. (2022) and Lu et al. (2023), and the research conclusions are consistent. This also answers the question at the beginning of this paper. With the continuous improvement of environmental regulation policies, environmental regulation is a powerful policy tool for the government to promote green development.

In addition, we find that technological innovation plays a positive mediating role in the impact of environmental regulation on green development. Environmental regulation can promote green development through technological innovation. The hypothesis H2 is strongly verified. Although the improvement of regional environmental regulation will increase the cost of enterprises, it also stimulates the innovation consciousness of enterprises. Enterprises can improve the technical level and enhance the market competitiveness by increasing the input of R&D. In the context of environmental regulation policies, the government will give certain tax incentives to enterprises with technological innovation, so as to reduce the innovation pressure of enterprises and improve the enthusiasm and creativity of technological innovation. Government environmental regulation has an impact on enterprises in the short term and reduces their profit margins. In the medium term, the overwhelmed enterprises will be eliminated by the market, and thus forced or voluntarily leave the market. In the long run, there are technical barriers to market access, and only enterprises with a certain ability of technological innovation can enter and survive. In order to enter the market, win market share and maintain competitive advantages, enterprises have to enhance their technological innovation capabilities. Further, the innovation of production process, on the one hand, can improve the input-output ratio of production factors, and then improve the profit margin of enterprises. On the other hand, it can improve the utilization rate of fossil energy, and ensure that the channels for enterprises to change from traditional energy to clean energy are smooth, so as to reduce the pollution emissions. To sum up, the product innovation of enterprises can meet the higher demand of consumers, improve the diversity of products, expand the market power of enterprises, and then improve the profit margin of enterprises. Finally, the production of more environmental protection technology products has accelerated the development of environmental protection industry in the long run. Through the above two ways, technological innovation enterprises not only create more benefits for the whole society and improve regional economic efficiency, but also improve regional environmental quality and enhance regional green development.

However, we find that environmental regulation mainly plays a direct role in green development, and the intermediate role of technological innovation is not obvious. This conclusion is contrary to some previous empirical studies (Guo et al., 2017). In order to find out the reasons, we explore the threshold role of technological innovation in environmental regulation affecting green development. It is found that when technological innovation is at a low level, it is not conducive to the promotion of green development. Only when technological innovation exceed the threshold, environmental regulations stimulate green creativity and promote green development. At the same time, high-energy-consuming enterprises are forced to withdraw from the market, and the remaining enterprises choose technological innovation to improve their core competitiveness. The technological innovation of the whole industry is in a spiraling upward trend, which will improve the regional green total factor productivity in the long run, and then promote green development. Research shows that in order to improve regional green development, on the one hand, it is necessary to strengthen the intensity of environmental regulation, and on the other hand, it is necessary to improve the level of regional technological innovation. Only when technological innovation exceeds a certain level can environmental regulation further stimulate the indirect role of green development through technological innovation. Finally, the threshold effect of technological innovation well explains the non-linear impact of environmental regulation on green development.

7 Conclusion and recommendations

7.1 Conclusion

This study presents a theoretical model that encompasses environmental regulation, technological innovation and green development, elucidating their intrinsic interplay. Then, the article assesses green development of China using 286 prefecture-level cities. We examines the disparities in the effects of regulations aimed at early emission reduction *versus* those focused on later governance, as well as regulations targeting sulfur dioxide and smoke (dust). Moreover, the article explores the indirect and threshold effects of technological innovation on the green development impact of environmental regulation. The findings are as follows.

(1) The impact of environmental regulation on green development follows a U shaped curve. It only promotes regional green development when the threshold value of environmental

regulation is exceeded. The results remain robust even after replacing the method of constructing environmental regulation and green development variables.

(2) The effects of classified policies show that later governance-oriented regulations and regulations on smoke (dust) have a significant U shaped effect on green development. The environmental regulation intensity of both needs to be moderately strengthened.
(3) Environmental regulation should be strengthened for the western region, Chengdu-Chongqing city cluster, the middle reaches of the Yangtze River city cluster, Medium-sized city and ultra-heavily polluted cities, and grasp the appropriate degree of environmental regulation for the eastern region, the Guangdong-Hong Kong-Macao Greater Bay Area, Yangtze River Delta city cluster, large and large cities, and heavy and moderately polluted cities. All above three findings support hypothesis H1.
(4) Environmental regulation can promote green development through technological innovation and green technology innovation, and the industrial structure plays a positive moderated effect. Compared with technological innovation, green technological innovation has a stronger effect on promoting green development, and environmental regulation is more likely to significantly improve green development through the interaction between green technological innovation and industrial structure.
(5) Environmental regulation mainly directly affects green development. The mediated role of technological innovation is not clear. This is because technological innovation plays a threshold role in the green development effect of environmental regulation. When technological innovation is at a low level, it is not conducive to improving green development. When technological innovation exceeds the threshold value of 0.01, environmental regulation promotes green development. The above two conclusions confirm hypothesis H2.

7.2 Recommendations

In view of the above conclusions, we put forward the following recommendations.

(1) Local governments should guide enterprises to thoroughly implement the concept of green development through environmental regulations, push enterprises to carry out green upgrading in production process and production technology, and then guide the transformation of economic development momentum, so as to realize the gradual replacement of traditional extensive growth mode by green and innovative high-quality economic development mode.
(2) The government should play the driving role of different environmental regulation policies on green development. For example, it should focus on supporting the late treatment type and smoke (powder) dust environmental regulation policies, including improving the policy system and promoting the transformation of the regulatory content to reality in order to give full play to its external effects. In addition, the government can further optimize the combination of environmental regulation tools, build a sustainable environmental regulation policy system, and accelerate the positive effect of environmental regulation.
(3) The government should fully consider regional differences, implementation conditions and environmental carrying capacity, build an environmental regulation system with a high degree of differentiation and strong regional suitability, and implement diversified environmental regulations according to local conditions. Refine environmental regulatory standards across regions, industries and enterprises. Combined with the environmental dependence of new enterprises and new projects, the entry threshold of polluting industries should be appropriately raised, and refined environmental regulation policies should be formulated. Effectively track the pollution intensity of key objects, and timely adjust the environmental regulation intensity according to the pollution intensity. Especially, strengthen environmental regulations vigorously in the western region, Chengdu-Chongqing city cluster, the middle reaches of the Yangtze River city cluster, medium-sized cities, and ultra-heavy pollution cities.
(4) The government should fully implement the innovation-driven strategy and deepen the supply-side reform in the field of scientific and technological innovation. For example, increase public investment to support and encourage enterprises to research and develop green technologies, improve production processes and install efficient cleaning equipment, and then vigorously develop new green industries. Absorb and gather resources of high-end innovation factors, cultivate high-level talents for technological innovation, and enhance our capacity for technology absorption and independent innovation. Optimize the environment for scientific and technological innovation, reform the rigid system that hinders scientific and technological innovation, and improve the supporting mechanism. Strengthen technological innovation, attach importance to the construction of infrastructure and platforms for technological innovation, establish a guidance and incentive mechanism for technological innovation, and improve the ability of independent technology research and development. Strengthen the introduction, digestion and re-absorption of advanced science and technology, and accelerate the commercialization and application of achievements. It is necessary to establish an insurance system for technological innovation so that technological innovation can better serve economic development. In addition, the government should strengthen the innovation investment in the transformation and recycling technology of smoke (powder) dust pollutants.
(5) The government should deepen the adjustment of industrial structure, accelerate the development of producer services, and accelerate the transformation and upgrading of the green structure of polluting industries. For example, improve the level of precise policies, reasonably guide enterprises to carry out cleaner production, and further promote the transformation of industrial structure from extensive development to green environmental protection. It is vital to support and promote the development of producer services and high-tech industries, give full play to the effect of upgrading their industrial structure, and promote green development and upgrading.

8 Limitations

There are still some limitations in this paper, which will be further studied in the future. Enterprises, not cities, are the direct targets of environmental regulation. With the gradual opening of the platform for obtaining micro-data, it can be studied from the perspective of industry or enterprise and from a longer period of time. The research envisaged above will help to draw more direct, effective and operational conclusions and provide accurate recommendations for promoting green development. Further research can make use of the mechanism design theory to evaluate the difference of green development effects of different types of environmental regulations for certain pollution medium (air, water, soil, ecosystem) and different impact ranges (global, watershed, local).

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://www.epsnet.com.cn/index.html#/Index.

Author contributions

FH: conceptualization, funding acquisition; YZa: data curation, model analyses, writing original draft; BF: software, visualisation; YZh: methodology, validation. 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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References

Acemoglu, D., Aghion, P., Bursztyn, L., and Hemous, D. (2012). The environment and directed technical change. *Am. Econ. Rev.* 102 (1), 131–166. doi:10.1257/aer.102.1.131

Brock, W. A., and Taylor, M. S. (2010). The green solow model. *J. Econ. Growth* 15 (2), 127–153. doi:10.3386/w10557

Chen, Q., Mao, Y., and Morrison, A. M. (2021). Impacts of environmental regulations on tourism carbon emissions. *Int. J. Environ. Res. Public Health* 18 (23), 12850. doi:10.3390/ijerph182312850

Cole, M. A., and Robert, J. R. (2003). Elliott do environmental regulations influence trade patterns? Testing old and new trade theories. *World Econ.* 26 (7), 1163–1186. doi:10.1111/1467-9701.00567

Dong, F., Zhang, S., Li, Y., Li, J., Xie, S., and Zhang, J. (2020). Examining environmental regulation efficiency of haze control and driving mechanism: Evidence from China. *Environ. Sci. Pollut. Res. Int.* 27 (23), 29171–29190. doi:10.1007/s11356-020-09100-9

Feng, Z., and Chen, W. (2018). Environmental regulation, green innovation, and industrial green development: An empirical analysis based on the spatial durbin model. *Sustainability* 10 (1), 223. doi:10.3390/su10010223

Ghosal, V., Stephan, A., and Weiss, J. F. (2019). Decentralized environmental regulations and plant-level productivity. *Bus. Strategy Environ.* 28 (6), 998–1011. doi:10.1002/bse.2297

Guo, L. l., Qu, Y., and Tseng, M. L. (2017). The interaction effects of environmental regulation and technological innovation on regional green growth performance. *J. Clean. Prod.* 162, 894–902. doi:10.1016/j.jclepro.2017.05.210

Hansen, B. E. (1999). Threshold effects in non-dynamic panels: Estimation, testing, and inference. *J. Econ.* 93 (2), 345–368. doi:10.1016/S0304-4076(99)00025-1

Hu, J., Pan, X., and Huang, Q. (2020). Quantity or quality? The impacts of environmental regulation on firms' innovation–Quasi-natural experiment based on China's carbon emissions trading pilot. *Technol. Forecast. Soc. Change* 158, 120122. doi:10.1016/j.techfore.2020.120122

Ji, J., Xie, Z., Li, C., and Ji, F. (2022). The influence of the manufacturing agglomeration heterogeneity on the green economic efficiency in China. *Electron. Commer. Res.* doi:10.1007/s10660-022-09641-w

Jiang, H. D., Purohit, P., Liang, Q. M., Dong, K., and Liu, L. J. (2022a). The cost-benefit comparisons of China's and India's NDCs based on carbon marginal abatement cost curves. *Energy Econ.* 109, 105946. doi:10.1016/j.eneco.2022.105946

Jiang, H. D., Xue, M. M., Liang, Q. M., Masui, T., and Ren, Z. Y. (2022b). How do demand-side policies contribute to the electrification and decarburization of private transportation in China? A CGE-based analysis. *Technol. Forecast. Soc. Change* 175, 121322. doi:10.1016/j.techfore.2021.121322

Lu, M., Daixu, L., Peng, W., and Ruiqi, M. (2023). Heterogeneous environmental regulation tools and green economy development: Evidence from China. *Environ. Res. Commun.* 5 (1), 015007. doi:10.1088/2515-7620/acb1f9

Luo, Y., Mensah, C. N., Lu, Z., and Wu, C. (2022). Environmental regulation and green total factor productivity in China: A perspective of Porter's and compliance hypothesis. *Ecol. Indic.* 145, 109744. doi:10.1016/j.ecolind.2022.109744

Manello, A. (2017). Productivity growth, environmental regulation and win–win opportunities: The case of chemical industry in Italy and Germany. *Eur. J. Operational Res.* 262 (2), 733–743. doi:10.1016/j.ejor.2017.03.058

Muller, D., Judd, C. M., and Yzerbyt, V. Y. (2005). When moderation is mediated and mediation is moderated. *J. Personality Soc. Psychol.* 89 (6), 852–863. doi:10.1037/0022-3514.89.6.852

Ouyang, X., Li, Q., and Du, K. (2020). How does environmental regulation promote technological innovations in the industrial sector? Evidence from Chinese provincial panel data. *Energy Policy* 139, 111310. doi:10.1016/j.enpol.2020.111310

Ren, X., Li, J., He, F., and Lucey, B. (2023b). Impact of climate policy uncertainty on traditional energy and green markets: Evidence from time-varying granger tests. *Renew. Sustain. Energy Rev.* 173, 113058. doi:10.1016/j.rser.2022.113058

Ren, X., Zeng, G., Dong, K., and Wang, K. (2023a). How does high-speed rail affect tourism development? The case of the sichuan-chongqing economic circle. *Transp. Res. Part A Policy Pract.* 169, 103588. doi:10.1016/j.tra.2023.103588

Ren, X., Zeng, G., and Zhao, Y. (2023c). Digital finance and corporate ESG performance: Empirical evidence from listed companies in China. *Pacific-Basin Finance J.* 79, 102019. doi:10.1016/j.pacfin.2023.102019

Selden, T. M., and Song, D. (1995). Neoclassical growth, the J curve for abatement, and the inverted U curve for pollution. *J. Environ. Econ. Manag.* 29 (2), 162–168. doi:10.1006/jeem.1995.1038

Shang, Y., Lyu, G., and Mi, Z. (2022). Green technology transfer, environmental regulation, and regional green development chasm: Based on the empirical evidence from Yangtze River Delta. *Int. J. Environ. Res. Public Health* 19 (21), 13925. doi:10.3390/ijerph192113925

Shi, B., Feng, C., Qiu, M., and Ekeland, A. (2018). Innovation suppression and migration effect: The unintentional consequences of environmental regulation. *China Econ. Rev.* 49, 1–23. doi:10.1016/j.chieco.2017.12.007

Song, M., Tao, W., and Shen, Z. (2022). Improving high-quality development with environmental regulation and industrial structure in China. *J. Clean. Prod.* 366, 132997. doi:10.1016/j.jclepro.2022.132997

Stiglitz, J. (1974). Growth with exhaustible natural resources: Efficient and optimal growth paths. *Rev. Econ. Stud. (Symposium)* 41, 123–137. doi:10.2307/2296377

Wang, H., Yang, M., He, R., and Zheng, P. (2022). Environmental regulation, foreign direct investment, and export sophistication of China: An empirical study based on dynamic system GMM and threshold model. *Environ. Sci. Pollut. Res. Int.* 29 (48), 72090–72100. doi:10.1007/s11356-021-14833-2

Wang, Y., and Shen, N. (2016). Environmental regulation and environmental productivity: The case of China. *Renew. Sustain. Energy Rev.* 62, 758–766. doi:10.1016/j.rser.2016.05.048

Watanabe, M., and Tanaka, K. (2007). Efficiency analysis of Chinese industry: A directional distance function approach. *Energy Policy* 35 (12), 6323–6331. doi:10.1016/j.enpol.2007.07.013

Xepapadeas, A., and de Zeeuw, A. (1999). Environmental policy and competitiveness: The porter hypothesis and the composition of capital. *J. Environ. Econ. Manag.* 37 (2), 165–182. doi:10.1006/jeem.1998.1061

Xu, X., Hou, P., and Liu, Y. (2022). The impact of heterogeneous environmental regulations on the technology innovation of urban green energy: A study based on the panel threshold model. *Green Finance* 4 (1), 115–136. doi:10.3934/gf.2022006

Yang, W., and Wang, M. (2022). Environmental regulation and green technology innovation: Incentive or disincentive effect? New evidence from resource-based cities in China [article; early access]. *Environ. Sci. Pollut. Res.* 30, 34440–34459. doi:10.1007/s11356-022-24185-0

Ye, T., Zheng, H., Ge, X., and Yang, K. (2021). Pathway of green development of Yangtze River economics belt from the perspective of green technological innovation and environmental regulation. *Int. J. Environ. Res. Public Health* 18 (19), 10471. doi:10.3390/ijerph181910471)

Zhan, L., Guo, P., and Pan, G. (2023). The effect of mandatory environmental regulation on green development efficiency: Evidence from China. *Environ. Sci. Pollut. Res. Int.* 30 (4), 9782–9792. doi:10.1007/s11356-022-22815-1

Zhang, M., Sun, R., and Wang, W. (2021). Study on the effect of public participation on air pollution control based on China's Provincial level data. *Environ. Dev. Sustain.* 23 (9), 12814–12827. doi:10.1007/s10668-020-01186-y

Zhao, H., Hu, J., Hao, F., and Zhang, H. (2022). Determinants of carbon dioxide emissions and their peaking prospect: Evidence from China. *Front. Environ. Sci.* 10, 913835. doi:10.3389/fenvs.2022.913835

Zhao, S., Jiang, Y., and Wang, S. (2019). Innovation stages, knowledge spillover, and green economy development: Moderating role of absorptive capacity and environmental regulation. *Environ. Sci. Pollut. Res. Int.* 26 (24), 25312–25325. doi:10.1007/s11356-019-05777-9

Zheng, Y., Wen, F., Deng, H., and Zeng, A. (2022). The relationship between carbon market attention and the EU CET market: Evidence from different market conditions. *Finance Res. Lett.* 50, 103140. doi:10.1016/j.frl.2022.103140

Zhong, S., Li, J., and Zhang, D. (2022). Measurement of green total factor productivity on Chinese pig breeding: From the perspective of regional differences. *Environ. Sci. Pollut. Res.* 29 (18), 27479–27495. doi:10.1007/s11356-021-17908-2

Zhou, Y., Zhu, S., and He, C. (2017). How do environmental regulations affect industrial dynamics? Evidence from China's pollution-intensive industries. *Habitat Int.* 60, 10–18. doi:10.1016/j.habitatint.2016.12.002