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The impact of environmental regulation on China's industrial green development and its heterogeneity

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The research analyzes the impact of environmental regulation on industrial green development using panel data from 30 provinces in China from 2006 to 2018. We employ the Super-slack-based measuring (SBM) model to measure the level of domestic industrial green development and use the ordinary panel model, the panel threshold model, and the spatial panel model for empirical estimation. The results reveal that the environmental regulation index plays a significant role in promoting such development. Environmental regulation index, command-and-control environmental regulation, market-incentive environmental regulation, and public-participation environmental regulation all have only a single threshold of technological progress and fiscal decentralization. Further analysis shows that China's industrial green development presents obvious spatial agglomeration characteristics, and there is a significantly positive spatial correlation between different environmental regulation indicators and industrial green development. Our findings provide useful policy recommendations for promoting industrial green development in China.

KEYWORDS

environmental regulation, industrial green development, technological progress, fiscal decentralization, heterogeneity

Introduction

China's industrial development process in recent years has been accelerating, and great achievements have been made. In 2020 its total industrial output value was 31.3 trillion yuan, or an increase of nearly 90% over 2010. However, for a long time, domestic industrial development has been excessively dependent on the input of resources and energy factors, emphasizing the expansion of output scale. Although this extensive development pattern has promoted rapid economic development, it has also led to serious environmental pollution problems (Zhu et al., 2019; Chen et al., 2020a,b;

Zhao et al., 2022a,b). In 2019 China's industry consumed about 66% of its energy and generated more than 85% of sulfur dioxide and dust. It can be seen that the realization of industrial growth is accompanied by huge environmental costs, and the deepening of its industrialization undoubtedly brings new challenges to the construction of ecological civilization.

The ninth sustainable development goal in the 2030 Agenda for Sustainable Development issued by the United Nations, which is to "Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation," points out the direction and presents arduous tasks for the future industrial development of countries. In fact, the China government attaches great importance to resource and environmental pollution issues and is committed to promoting sustainable industrial development. The country has proposed five development concepts of innovation, coordination, greenness, openness, and sharing and has issued a series of relevant laws and regulations to support industrial green development. In addition, the goal of peak carbon emissions by 2030 and achieving carbon neutrality by 2060 has also strengthened China's industrial commitment to green and low-carbon development (Zhao et al., 2022c,d). In this context, the domestic industry urgently needs to transform to green production, reduce excessive resource consumption and pollutant emissions, and contribute to global pollution control and the realization of sustainable development goals (Yang et al., 2022; Zhang et al., 2022). However, effectively coordinating the relationship between industrial development and environmental protection is a major problem to be solved urgently.

Due to the negative externality of environmental pollution, it is difficult to achieve effective regulation of pollution emissions only based on spontaneous market regulation (Sun et al., 2021; Chen et al., 2022). Therefore, government intervention in pollution control and environmental protection is particularly important (Wang and Liu, 2019). Environmental regulation, as the main policy tool for the government to prevent pollution emissions, is of great significance to realize sustainable development of economy and environment (Ma and Xu, 2022). On the one hand, the implementation of environmental regulations will increase the production cost of enterprises by levying pollutant discharge fees, prompting enterprises to reduce the use of high-polluting production factors and adopt clean energy, thus achieving the goal of reducing pollution emissions (Zhang et al., 2019). On the other hand, environmental regulation will promote enterprises to carry out technological research and development and improve the level of green technology and production efficiency (Porter and Van der Linde, 1995). In addition, strict environmental regulations will not only squeeze the profit space of highly polluting enterprises and force them to withdraw from the market, but also strengthen the development of environmentally friendly enterprises and contribute to the upgrading of industrial structure. Most scholars point out that environmental regulation has been effective in improving energy efficiency and addressing the externalities of environmental pollution (Mandal, 2010; Neves et al., 2020; Chen et al., 2022).

The Chinese government in recent years has issued a series of environmental regulatory measures aimed at reducing industrial pollution emissions and achieving sustainable development through environmental regulation (Zhang et al., 2019). However, it can be found that China's environmental quality seems to continue to deteriorate, and industrial emissions are still the main cause of environmental problems. Moreover, through in-depth research, especially after the green paradox theory was put forward, scholars are questioning the necessity and effectiveness of environmental regulation at improving environmental quality (Sinn, 2008; Van der Werf and Di Maria, 2012). Due to the imbalance of its industrial development, there are great differences in the degree of pollution emissions, which in turn result in different effects of environmental policies. In addition, the implementation of environmental regulation policies may also lead to the relocation of industries in different regions, further complicating the industrial pollution situation in China. So can environmental regulation effectively promote China's industrial green transformation? This question has not been adequately answered. Therefore, it is necessary to clearly identify the role and influence mechanism of environmental regulation in industrial green transformation, which is of great significance for China to take further policy measures to promote industrial green transformation.

At present, scholars have conducted extensive discussions on environmental issues and provided useful evidence. However, the existing research still has the following shortcomings. First, there is no consensus on the impact of environmental regulation on environmental performance, and the existing literature on environmental performance focuses on the fields of agriculture and manufacturing (Chen et al., 2021; Chen and Zhu, 2022). There is still a lack of research on green development in the industrial sector. The development of industry is an important factor leading to environmental problems, so it is necessary to expand research on the industrial field. Second, although relevant literatures have investigated the nonlinear characteristics of environmental regulation on green innovation and pollution emission (Chen et al., 2019; Song et al., 2020), these studies seldom consider the interference of external factors and cannot identify the inflection point values. The influence of environmental regulation on industrial green development is a dynamic and complex process, which is restricted by technical conditions and institutional environment. This makes it possible that the effect has threshold characteristics. Third, most studies assume that regions are independent of each other, while ignoring the spatial correlation between economic variables in different regions, making it difficult to comprehensively analyze the spatial effect of environmental regulation on industrial green development.

We therefore adopt the threshold model and spatial econometric model to explore the relationship between environmental regulation and industrial green development in China. The main contributions of this study can be summarized as follows. First, we subdivide the types of environmental regulations, and deeply explore the differences in the impact of various environmental regulations on industrial green development, so as to provide useful supplements to existing research. Second, our study takes technological progress and fiscal decentralization as threshold variables to analyze the nonlinear effects of different types of environmental regulations on industrial green development. Third, considering the spatial dependence characteristics of regional industrial green development, this study further examines the spatial effects of different types of environmental regulations on industrial green development, thus providing a reference for the government to effectively implement joint governance policies for regional pollution.

The remaining contents of this study are arranged as follows. The second part reviews the relevant literature. The third part involves model setting, variable measurement and data description. The fourth part analyzes the empirical results. The fifth part summarizes the research results and puts forward policy suggestions. The sixth part is to clarify the limitations of the research and future research directions.

Literature review

Existing research views on the relationship between environmental regulation and environmental performance have not yet reached a consensus, but mainly offer three viewpoints.

First, most studies in the literature have noted that environmental regulation has a positive effect on environmental performance. Shapiro and Walker (2018) pointed out that environmental regulation promotes the adoption of emission reduction technologies, which is the main reason to explain the reduction of manufacturing pollution emissions. Hashmi and Alam (2019) examined the impact of environmental technologies and regulations on carbon emissions, and found that environmental regulations were more effective in reducing carbon dioxide emissions than environmental technologies, with a 1% increase in per capita environmental taxation and a 0.03% reduction in carbon dioxide emissions. Ulucak et al. (2020) took Brazil, India, China, Russia, and South Africa as research objects, and confirmed the positive role of environmental regulations in mitigating carbon emissions – that is, current environmental regulations are effective in achieving pollution reduction goals in these countries. Sun et al. (2021) recognized that environmental regulation not only increases the number of innovative products in high-tech industries, but also helps to improve the quality of innovative products, thus achieving a win-win situation for economic development and environmental governance. Cai et al. (2020) clarified that direct environmental regulation significantly stimulates green technology innovation in heavily polluting industries, and this impact is heterogeneous – that is, direct environmental regulation has a more obvious effect on green technology innovation of state-owned listed companies in heavy pollution industries and technology-capital-intensive industries.

You et al. (2019) concluded that without the influence of the government's political system, environmental regulation can significantly facilitate the ecological investment and ecological planning innovation of industrial enterprises, which add great significance to the sustainable development of China's economy. Liao and Shi (2018) discussed the positive effect between public appeal and green investment and showed that public appeal encourages local governments to adopt stricter environmental regulation measures, which are conducive to guiding enterprises to increase the research and development of clean technologies and green products. Wang et al. (2021) found that formal environmental regulation alleviates local air pollution by transferring polluting industries, while informal environmental regulation indirectly suppresses air pollution by improving formal environmental regulation measures. Wang et al. (2022) showed that all three types of environmental regulations have effectively contributed to the upgrading of China's industrial structure, among which the market-incentivized environmental regulation has a more significant role in promoting the industrial structure. Yu and Wang (2021) suggested that environmental regulation policy accelerates the change of regional industrial structure, and the legislative supervision and economic incentive of environmental regulation play a stronger role in explaining the upgrading of industrial structure.

Second, some studies have also suggested that environmental regulation may negatively affect environmental performance. The enhancement of environmental regulation increases the production cost of enterprises, which may eventually inhibit the upgrading of industrial structure (Jaffe and Palmer, 1997; Wang et al., 2022). Millimet et al. (2009) explored the economic impact of environmental regulation on different aspects of the market structure and acknowledged that environmental regulation increases enterprises' production cost, thus squeezing their profit margins and reducing their production efficiency. This will affect the entry and exit behavior of enterprises and ultimately have a negative impact on the industrial structure. Sinn (2008) noted that if fossil fuel suppliers feel a potential threat from the gradual implementation of national environmental policies, then they will extract fossil fuel reserves at a faster rate, thereby accelerating global warming. Van der Werf and Di Maria (2012) showed that imperfect environmental policies may give rise to the "green paradox" – that is, the well-intended policies encourage resource owners to increase resource extraction due to insufficient subsidies for alternative energy sources and a lag in implementation, resulting in an increase in current pollution emissions rather than a decrease.

He et al. (2022) pointed out that under the influence of fiscal decentralization, in order to maximize their own interests, local governments engage in "race to the bottom" when formulating and implementing environmental regulation policies, which is not conducive to reducing agricultural carbon emission intensity. Zhang et al. (2021) noticed that local governments in China have diversified competitive behaviors in the implementation of environmental regulations, which lead to the transfer of pollution to nearby areas and increase local carbon dioxide emissions. Moreover, this study also proves that China's current environmental regulation is still in the stage of "green paradox". Millimet and Roy (2016) emphasized that due to the differences in environmental standards between different regions, polluting enterprises move from areas with strict environmental requirements to areas with lax environmental regulations, leading to continuous deterioration of environmental quality in the transferred areas. Kheder and Zugravu (2012) provided evidence for the pollution haven hypothesis by analyzing the impact of environmental regulations on the site selection of French manufacturing firms. They argued that manufacturing in France is more likely to locate in other countries with looser environmental regulations, making them potentially pollution havens. The effect of environmental regulation is also disturbed by external factors. You et al. (2019) believed under the influence of the fiscal decentralization system and political promotion championships that environmental regulation has a significant inhibitory effect on ecological innovation, ecological planning innovation, and ecological investment.

Third, different from the above two viewpoints, some studies pointed out that the relationship between environmental regulation and environmental performance is uncertain or exhibits nonlinear characteristics. Hao et al. (2018) mentioned that the current environmental regulation methods implemented in China have not achieved the expected results and proved that environmental regulation is only effective in curbing pollution emissions when foreign direct investment is controlled. Ren et al. (2018) used the STIRPAT model to examine the impact of environmental regulation on eco-efficiency and found heterogeneity in the influence of different types of environmental regulation on eco-efficiency. Xie et al. (2017) proved a non-linear relationship between command-and-control and market-based environmental regulations and green productivity, and the growth effect of green productivity driven by market-based environmental regulation is much stronger than that of command- and-control regulation. Du et al. (2021) believed that when the level of economic development is low, environmental regulation has no significant impact on the upgrading of industrial structure and also inhibits green technology innovation. Only when the level of economic development is relatively high will environmental regulation significantly promote green technology innovation and industrial structure upgrading, thereby accelerating the process of economic green transformation (Chen et al., 2020a,b; Zou et al., 2022).

The research of Song et al. (2020) confirmed the U-shaped relationship between environmental regulation and green product innovation. As the intensity of environmental regulation increases, its effect on green product innovation shifts from inhibition to promotion. Zhang et al. (2020) believed that environmental regulation has a non-linear impact on carbon emissions. The improvement of environmental regulation makes the reduction effect of the total amount and intensity of carbon emissions more obvious, and foreign direct investment under the constraints of environmental regulation also inhibits carbon emissions. Chen et al. (2019) noted that environmental regulation and industrial structure have obvious non-linear effects on carbon dioxide emissions – that is, the impact of environmental regulation on carbon emissions changes with the rationalization of industrial structure. Wu et al. (2020a) confirmed a U-shape relationship between environmental regulation and green total factor energy efficiency, which means that the expansion of environmental governance decentralization has effectively improved local governments' autonomous choices for pollution control. Chen and Qian (2020) found that various types of marine environmental regulation have a positive U-shape relationship with the upgrading of the manufacturing industry structure and the transfer of polluting industries, in which the inflection point of industrial structure upgrading occurs later than the transfer of polluting industries.

Materials and methods

Model setting

Baseline regression model

Considering the volatility of green development level, this study draws on the research of Li and Wu (2017), and firstly constructs an ordinary panel data model to explore the impact of environmental regulations on the level of industrial green development as follows.

$$y_{it} = \beta_0 + \mu_i + \lambda_t + x'_{it}\beta_1 + k'_{it}\beta_2 + \varepsilon_{it}, \quad (1)$$

where i denotes province and t denotes year; y_{it} denotes industrial green development level; x_{it} denotes environmental regulation; k_{it} denotes a series of control variables; β_1 and β_2 denotes regression coefficients of core explanatory variables and control variables, respectively; μ_i and λ_t denotes individual effects and time effects, respectively; and ε_{it} is a random disturbance term.

Threshold regression model

As the impact of environmental regulation on industrial green development is a complex and dynamic process, which is easily disturbed by external factors such as technologies and policies. On the one hand, most scholars have confirmed that technological progress is a key link in achieving green development (Kang et al., 2018; Xie et al., 2020), and the effects of environmental regulation are closely related to the level of green technologies in enterprises (Ren and Ji, 2021). Therefore, it is necessary to analyze the role of technological progress in the impact of environmental regulation on industrial green development. On the other hand, the impact of environmental regulation on environmental quality is inseparable from institutional constraints (Chen and Chang, 2020; Wu et al., 2020b). Wu et al. (2020a) believe that the effect of environmental regulation on energy efficiency is closely related to environmental decentralization, and there are significant differences in the role of different types of environmental management decentralization. It can be seen that environmental regulation may have threshold characteristics in the process of acting on industrial green development. When technological progress or fiscal decentralization are on both sides of the threshold, the effect may jump or even reverse.

Therefore, we refer to the research of Wang and Shao (2019) and Wu et al. (2020a) to analyze the nonlinear characteristics of environmental regulation affecting industrial green development from the perspective of technological progress and fiscal decentralization. On this basis, drawing on relevant studies by Hansen (2000), the following threshold regression model is constructed.

$$y_{it} = \beta_0 + \mu_i + \lambda_t + x'_{it}\beta_{11} \cdot I\left(q_{it} \le \gamma_1\right) + x'_{it}\beta_{12} \cdot I\left(\gamma_1 < q_{it} \le \gamma_2\right) + \cdots + x'_{it}\beta_{1n+1} \cdot I\left(q_{it} > \gamma_n\right) + k'_{it}\beta_2 + \varepsilon_{it} \tag{2}$$

where $I(\cdot)$ denotes the indicator function; q_{it} denotes the threshold variable; and γ_i denotes the threshold value.

Spatial econometric model

The panel model constructed above assumes that regions are independent of each other, while in fact any economic variable in one region is often influenced by neighboring regions. Spatial autocorrelation is a common phenomenon in ecological data that affects the estimation and inference of statistical models (Legendre, 1993; Kissling and Carl, 2008). Hu and Wang (2020) emphasized that environmental regulation and environmental performance have obvious spatial attributes, and the results that ignore spatial correlation may be biased. Some scholars have conducted a spatial econometric analysis of the relationship between environmental regulation and pollution emissions, indirectly confirming the existence of this spatial correlation (Feng et al., 2020; Liu et al., 2022). Therefore, we further construct a spatial panel model to investigate the spatial effect of environmental regulation on industrial green development. The spatial correlation test is a prerequisite for spatial model regression. Referring to the study of Feng et al. (2020), we select global *Moran's I* index to test whether the impact of heterogeneous environmental regulation on industrial green development is spatially dependent. The specific formula is as follows.

$$Moran's\ I = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} w_{ij}(y_i - \bar{y})(y_j - \bar{y})}{s^2 \sum_{i=1}^{N}\sum_{j=1}^{N} w_{ij}} \tag{3}$$

$$s^2 = \frac{1}{N}\sum_{i=1}^{N}(y_i - \bar{y})^2,$$

where y_i and y_j are the variable values of province i and province j, respectively; N represents the total number of regions; $\bar{y}$ represents the sample mean; and w_{ij} is the adjacency space weight matrix. The values of *Moran's I* index range from [−1, 1], indicating positive spatial correlation when it is greater than 0, negative spatial correlation when it is less than 0, and no spatial correlation when it is equal to 0.

The commonly used spatial econometric models mainly include the spatial lag model (SAR), spatial error model (SEM), and spatial Durbin model (SDM). Since SDM is the most general and widely used form, we adopt SDM for empirical testing based on the research of LeSage and Pace (2009). The specific form is as follows.

$$y_{it} = \rho\sum_{j=1}^{N} w_{ij}y_{jt} + x'_{it}\beta + \sum_{j=1}^{N} w_{ij}x'_{jt}\delta + \mu_i + \lambda_t + \varepsilon_{it}, \tag{4}$$

where $\sum_{j=1}^{N} w_{ij}x_{jt}\delta$ denotes the spatial lagged explanatory variables of neighboring regions; N denotes the total number of regions; ρ denotes the spatial autoregressive coefficients; β and δ denote the parameters to be estimated; and other variables have the same meanings as above.

Variable description

Calculation of industrial green development level

Given that data envelopment analysis (DEA) can deal with multiple input and multiple output problems, this study uses a Super-slack-based measuring model (Super-SBM model) model containing undesirable outputs to measure the industrial green development level by referring to the relevant research of Tone (2002). The specific form is as follows.

$$\rho^* = \min \frac{\frac{1}{m}\sum_{i=1}^{m}\frac{\bar{x}}{x_{i0}}}{\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{\bar{y}}{y_{r0}} + \sum_{q=1}^{s_2}\frac{\bar{z}}{z_{q0}}\right)} \quad (5)$$

$$s.t.\begin{cases} \bar{x} \geq \sum_{j\neq 1 \neq 0}^{n} \lambda_j x_{ij} \\ \bar{y} = \sum_{j\neq 1 \neq 0}^{n} \lambda_j y_{ij} \\ \bar{z} = \sum_{j\neq 1 \neq 0}^{n} \lambda_j z_{ij} \\ \lambda > 0, j = 1, 2, \ldots, n, and\, j \neq 0 \\ \bar{x} \geq x_{i0} \\ \bar{y} \geq y_{r0} \\ \bar{z} \geq z_{q0} \\ i = 1, 2, \ldots, m; r = 1, 2, \ldots, s; q = 1, 2, \ldots, k \end{cases},$$

where ρ^* denotes the efficiency value; n denotes the number of decision units; m, s_1, and s_2 denote the number of input, desirable output, and undesirable output indicators, respectively; x_{ij}, y_{ij}, and z_{ij} denote the input, desirable output, and undesirable output variables of the evaluated units, respectively; and $\bar{x}$, $\bar{y}$, and $\bar{z}$ denote the slack variables of input, desirable output, and undesirable output, respectively.

Combining with related studies, we choose capital stock, total number of employees at the end of the year, and total energy consumption as input indicators, industrial value added as desirable output, and industrial wastewater emissions, industrial solid waste emissions, industrial sulfur dioxide emissions, and industrial carbon dioxide emissions as undesirable outputs.

Calculation of environmental regulation

According to the different subjects of implementing environmental regulation policies, environmental regulation is subdivided into command-and-control environmental regulation (*ERC*), market-incentive environmental regulation (*ERM*), and public-participation environmental regulation (*ERP*). Among them, the command-and-control environmental regulation is measured by the amount of completed investment in industrial pollution control, the market-incentive environmental regulation is represented by pollutant discharge fees and environmental taxes, and the public-participation environmental regulation is measured by the number of proposals made by the National People's Congress. On this basis, the overall environmental regulation index (*ER*) is obtained by using the entropy method and taken as a proxy variable for environmental regulation. A higher value of environmental regulation index means a higher intensity of environmental regulation.

Control variables

The control variables selected in this study include the following. Total actual utilized foreign investment is chosen to measure the foreign direct investment (*FDI*), so as to examine the influence of foreign investment on the level of industrial green development. Referring to the work of Shan and Zhang (2018), the coordination coefficient between industry and employment structure is measured as a proxy variable of industrial coordination degree (*IC*), and the indicators used involve the ratio of the added value of the tertiary industry to the total output value, as well as the proportional relationship between the employment of the tertiary industry and the total employment. Energy structure (*ES*) is captured by the share of coal consumption in total energy consumption. The comprehensive utilization rate of industrial solid waste is taken to measure the resource recycling level of industrial enterprises (*RC*). The ratio of total urban population at the end of the year to land area is selected to evaluate population density (*PD*). Technological progress (*TI*) is measured by the number of patent applications in the region. Fiscal decentralization (*FD*) is measured by the ratio of per capita local fiscal expenditure to per capita central fiscal expenditure.

Data sources

Considering data availability, this study selects panel data of 30 provinces in China from 2006 to 2018 (These provinces refer to provincial administrative units, including provinces, municipalities and ethnic minority autonomous regions, Tibet, Taiwan, Hong Kong, and Macao are not included in the scope of this analysis). The data of each indicator are obtained from China Statistical Yearbook, China Industrial Economic Statistical Yearbook, China Environmental Statistical Yearbook, China Energy Statistical Yearbook, the statistical yearbooks of each province, and the EPS database. To alleviate and eliminate the possible heteroscedasticity without changing the time-varying characteristics of the original data, we perform logarithmic processing on all variables. The descriptive statistical results of variables appear in **Table 1**.

Empirical results and analysis

Baseline regression results

The random effects model and fixed effects model are respectively used for the empirical test, and **Table 2** lists the results. From the results of the Hausman test, the P-statistic values are 0.6861 and 0.1061, respectively, indicating that the research model does not reject the original hypothesis of using random effects. Therefore, we focus on the estimation results of the random effects model.

TABLE 1 Descriptive statistics of variables.

Variable	*N*	Mean	Standard deviation	Min	Max
ln *IGTFP*	390	−1.2145	0.7976	−3.4336	0.15192
ln *ER*	390	9.2624	1.0683	0.0000	10.9749
ln *ERC*	390	11.8425	0.9810	8.1783	14.1636
ln *ERM*	390	10.6416	0.9481	7.4951	12.5312
ln *ERP*	390	4.8999	1.0711	0.0000	7.0867
ln *FDI*	390	5.2904	1.6354	−1.2203	7.7219
ln *IC*	390	−0.1996	0.1489	−0.7337	−0.0008
ln *ES*	390	−0.4805	0.4752	−3.6082	0.5485
ln *RC*	390	−0.4569	0.3086	−1.3707	−0.0017
ln *PD*	390	5.4799	1.2936	2.0660	8.3157
ln *TI*	390	10.0300	1.5852	5.7838	13.5846
ln *FD*	390	0.1667	0.3875	−0.5317	1.3103

Before the inclusion of control variables, the coefficients for the effect of environmental regulation on industrial green development in model (1) and model (2) are 0.1850 and 0.1926, respectively, and both are significant at the 1% level. This indicates that environmental regulation has a significant contribution to industrial green development when the influence of other factors is not considered, and every 1% increase in environmental regulation causes at least a 0.1850% increase in industrial green development. From the regression results of model (3) and model (4), after adding the control variables, the coefficients of environmental regulation on industrial green development become 0.0840 and 0.0844, and both of them pass the 5% significance level test – that is, every 1% increase in environmental regulation raises the level of industrial green development by at least 0.0840%. Although the influence coefficient of environmental regulation decrease, its significant contribution does not change. When the intensity of environmental regulation is strengthened, industrial enterprises face considerable environmental penalty costs, which motivate them to increase investment in energy-saving equipment and clean technology R&D, thus promoting industry's green development. As we know, the formulation and implementation of environmental regulation have a cost effect, which may squeeze out the funds needed for R&D by industrial enterprises. At the same time, there is also an innovation compensation effect, which forces enterprises to improve resource utilization and expected output through technological innovation. Therefore, the effect of environmental regulation is the result of the game of two opposing forces. From the baseline regression results, it is clear that the innovation compensation effect of environmental regulation is greater than the compliance cost effect, thereby significantly promoting China's industrial green development.

In terms of the control variables, the coefficient of industrial coordination is significantly positive at the 5% level, suggesting that the higher the industrial coordination is, the more conducive it is to the industrial green development. This is because a reasonable industrial structure and employment structure help optimize factor allocation and promote green development efficiency through the technological linkage between industries (Zhao et al., 2016). The coefficient of resource recycling is significantly positive at the 5% level, which indicates that the improvement of resource recycling efficiency is conducive to reducing undesired outputs such as industrial waste and convert them into desired outputs, which in turn promote the development of industrial green transformation. This is also an important reason for the long-term implementation of circular economy development in China. The coefficient of technological progress is also significantly positive, meaning that technological progress contributes to industrial green development. As the core driving force of industrial transformation and upgrading, technological progress implies the transformation of traditional

TABLE 2 Results of the impact of environmental regulation on industrial green development.

Variable	RE model (1)	FE model (2)	RE model (3)	FE model (4)
ln *ER*	0.1850*** (0.0562)	0.1926*** (0.0637)	0.0840** (0.0368)	0.0844** (0.0361)
ln *PD*			−0.1036 (0.0865)	0.9922 (1.0001)
ln *IC*			1.6380** (0.7136)	1.9826** (0.7468)
ln *RC*			0.3790** (0.1680)	0.4073** (0.1811)
ln *FDI*			−0.0198 (0.0667)	0.0028 (0.0676)
ln *TI*			0.1842*** (0.0611)	0.1369* (0.0690)
ln *FD*			0.2212 (0.4219)	−0.2391 (0.4833)
ln *ES*			−0.2926 (0.3040)	−0.2784 (0.3974)
Constant	−2.9284*** (0.5373)	−2.9986*** (0.5902)	−2.8445*** (0.9993)	−8.3339 (5.2753)
Hausman	0.75 [0.6861]		14.48 [0.1061]	
N	390	390	390	390
R^2	0.0732	0.0732	0.2963	0.306

***, **, and * Represent significance at the 1, 5, and 10% levels, respectively. The value in ( ) is the standard error; the value in [ ] is the probability of accepting the null hypothesis.

production methods and the improvement of enterprise production efficiency, thus promoting the green transformation and development of the entire industry. In addition, the effects of fiscal decentralization, population density, foreign direct investment, and energy structure on industrial green development fail to pass the significance test.

Robustness test

To verify the robustness of the above findings, this study re-tests the research model by subdividing regions and environmental regulation indicators. The results appear in Tables 3, 4. Table 3 reports the results of the subregional robustness test. On the one hand, due to the regional differences in China's economic development level and resource endowment, we divide China into the eastern regions and the central and western regions, and examine the impact of environmental regulations on industrial green development in different regions. On the other hand, we calculate the average value of industrial added value in each province during the sample period, and divide the sample data into strong industrial provinces and weak industrial provinces according to the median. From the regression results of models (1)–(4) in Table 3, environmental regulation has shown a significant role in promoting industrial green development in different regions, which means that the above findings are robust.

Table 4 reports the robustness test results of the sub-indicators and replacement methods. On the one hand, environmental regulation is subdivided into command-and-control environmental regulation, market-incentive environmental regulation, and public-participation environmental regulation. We then examine the impact of the three types of environmental regulations on industrial green development. The results of models (1)–(3) in Table 4 show that the coefficients of all three types of environmental regulations are significantly positive at least at the 5% level – that is, they all significantly contribute to industrial green development. This finding is consistent with the baseline regression.

On the other hand, considering the possible endogeneity issue, the two-stage least squares regression is performed by selecting one lag period (Z_1) and two lag periods (Z_2) of the core explanatory variables as instrumental variables. Table 4's models (4)–(7) report the relevant regression results. From the results of the first stage, the instrumental variables highly correlate with the endogenous variables, and environmental regulation shows a tendency to strengthen from year to year. From the results of the second stage, the values of KP rk LM-statistic are 81.410 and 67.988, respectively, and the P-values of the LM test are both 0.0000, which reject the original hypothesis and indicate that the choice of instrumental variables is reasonable. The values of KP rk wald F-statistic are 348.156 and 174.573, respectively, which are much larger than the empirical statistics value of 10, indicating that both Z_1 and Z_2 pass the weak instrumental variable test. Therefore, it can be considered that the selection of the two instrumental variables satisfies the necessary conditions. Specifically, the coefficients of the two instrumental variables are 0.1186 and 0.2607, respectively, and are significant at least at the 10% level, which means that environmental regulation still significantly promotes industrial green development after replacing the regression method. The above results once again confirm the robustness of the findings herein.

Threshold test

We further select technological progress and fiscal decentralization as threshold variables and apply a panel threshold model to explore the nonlinear characteristics of heterogeneous environmental regulations affecting industrial green development. The premise for conducting the threshold model test is that a threshold effect must exist. Therefore, this study uses the bootstrap self-sampling method to examine the significance level and the specific threshold value of the threshold effect.

Threshold effect of technological progress

Table 5 reports the results of the threshold effect of technological progress for each variable. From the environmental regulation index, the F-statistic for its single threshold of technological progress is significant, while the F-statistic for the double threshold is not significant, indicating that there is only a single technological progress threshold for the impact of environmental regulation on industrial green development with a threshold value of 8.7494. From the perspective of the three types of environmental regulation, the single technological progress thresholds of command-and-control environmental regulation, market-incentive environmental regulation, and public-participation environmental regulation all exist, and none of them pass the double-threshold test. The single threshold values are 8.7494, 8.7494, and 10.9373, respectively. It can be seen that the technological progress threshold values of command-and-control environmental regulation and market-incentive environmental regulation are the same as that of the environmental regulation index, while the threshold value of public-participation environmental regulation is higher. Possible explanations for this result are as follows. Currently, environmental regulation is dominated by command-and-control environmental regulation and market-incentive environmental regulation, while public-participation environmental regulation shows a great difference from the other two kinds of environmental regulation. Thus, the impact of technological progress is inconsistent.

On the basis of the above analysis, the threshold model regression is performed for a single threshold of technological

TABLE 3 Regional robustness test results.

Variable	Regional location		Industrial development level	
	(1) Eastern	(2) Central and western	(3) Weak industry	(4) Strong industry
ln *ER*	0.1767* (0.0994)	0.0449** (0.0215)	0.0580* (0.0332)	0.2272** (0.0903)
ln *PD*	0.0591 (0.3520)	−0.0911 (0.1100)	−0.1678 (0.1657)	0.0551 (0.2201)
ln *IC*	7.7773*** (2.9406)	1.9425*** (0.4129)	0.8570 (1.0183)	2.4291 (1.4848)
ln *RC*	−0.5288* (0.3076)	0.5785*** (0.1568)	0.5324*** (0.1674)	0.1036 (0.2211)
ln *FDI*	−0.1783 (0.1475)	−0.0390 (0.0705)	0.0402 (0.0829)	−0.0852 (0.0930)
ln *TI*	−0.1225 (0.1444)	0.2119*** (0.0582)	0.2970** (0.1166)	0.0836 (0.0759)
ln *FD*	0.0579 (0.8319)	0.0193 (0.4321)	0.4623 (0.5030)	−0.3113 (0.5338)
ln *ES*	−1.1073*** (0.1183)	0.5095* (0.2681)	−0.3110 (0.2878)	0.0169 (0.2962)
Constant	−0.9983 (2.8981)	−2.1303*** (0.6765)	−3.7764*** (1.2345)	−3.5675 (2.3021)
N	143	247	195	195
R^2	0.4096	0.4230	0.4050	0.1869

***, **, and * Represent significance at the 1, 5, and 10% levels, respectively. The value in ( ) is the standard error.

TABLE 4 Robustness test results of sub-indicators and replacement methods.

Variable	Variable division			Instrumental variable method (2SLS)			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	ln *IGTFP*			ln *ER*	ln *IGTFP*	ln *ER*	ln *IGTFP*
ln *ERC*	0.1156*** (0.0388)						
ln *ERM*		0.2061** (0.0875)					
ln *ERP*			0.1095*** (0.0355)				
Z_1				0.8051*** (0.0431)			
Z_2						0.7079*** (0.0536)	
ln *ER*					0.1186*** (0.0412)		0.2607* (0.1392)
Control variable	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	−3.2874*** (0.9878)	−3.9507*** (1.3862)	−2.5135*** (0.8707)	1.1440*** (0.3114)	−3.8423*** (0.8988)	1.7131*** (0.4836)	-3.3010*** (0.9694)
KP rk LM-statistic				81.410		67.988	
LM *P*-value				0.0000		0.0000	
KP rk Wald *F*-statistic				348.156		174.573	
N	390	390	390	358	358	328	328
R^2	0.2997	0.3126	0.2979	0.6772	0.1838	0.6403	0.1706

***, **, and * Represent significance at the 1, 5, and 10% levels, respectively. The value in ( ) is the standard error.

progress, and the results are in Table 6. Table 6's model (1) presents the technological progress threshold effect of the environmental regulation index. When the technological progress is in the low threshold range, the effect of environmental regulation on industrial green development is small, and its value is only 0.0679. When technological progress continues to rise to the high threshold range, the regression coefficient of environmental regulation on industrial green development increases significantly to 0.1183. The reason is that the implementation of environmental regulations squeezes out the R&D investment of industrial enterprises, while technological innovation is characterized by high investment cost, long cycle time and high risk. When the level of technological progress is low, most enterprises can only manage from the pollution side of things due to constraints of capital and technology. Although the total amount of industrial pollution emissions is controlled to a certain extent, the technological progress of the whole industry is hindered, resulting in

TABLE 5 Test of the threshold effect of technological progress.

Variable	Threshold type	Threshold value	*F*-value	*P*-value	95% confidence interval
ln *ER*	Single	8.7494	24.17	0.0340	[8.6513, 8.7622]
	Double	10.9373	10.14	0.4180	[10.8725, 10.9558]
ln *ERC*	Single	8.7494	22.94	0.0620	[8.6513, 8.7622]
	Double	10.9373	10.73	0.4180	[10.8725, 10.9558]
ln *ERM*	Single	8.7494	20.45	0.0610	[8.6513, 8.7622]
	Double	10.9373	9.84	0.3620	[10.8675, 10.9558]
ln *ERP*	Single	10.9373	23.62	0.0460	[10.8831, 10.9558]
	Double	9.8447	14.24	0.1990	[9.6993, 9.8569]

TABLE 6 Regression results of the technological progress threshold model.

Variable		Threshold variable: technological progress			
		(1)	(2)	(3)	(4)
ln *ER*	ln *TI* < 8.7494	0.0679* (0.0375)			
	ln *TI* > 8.7494	0.1183*** (0.0361)			
ln *ERC*	ln *TI* < 8.7494		0.1058*** (0.0374)		
	ln *TI* > 8.7494		0.1436*** (0.0388)		
ln *ERM*	ln *TI* < 8.7494			0.2223*** (0.0609)	
	ln *TI* > 8.7494			0.2615*** (0.0590)	
ln *ERP*	ln *TI* < 10.9373				0.1129*** (0.0331)
	ln *TI* > 10.9373				0.0430 (0.0418)
Control variable		Yes	Yes	Yes	Yes
Constant		−9.7770* (5.0932)	−10.0450* (5.1673)	−9.8051** (4.7331)	−9.7598** (4.6096)
N		390	390	390	390
R^2		0.3472	0.3477	0.3560	0.3472

***, **, and * Represent significance at the 1, 5, and 10% levels, respectively. The value in ( ) is the standard error.

a slow process of industrial green development. When technological progress reaches a high level, the implementation of environmental regulations encourages enterprises to shift from pollution-end governance to production-end governance – that is, to reduce undesired output by using clean technologies and energy-saving equipment, thereby vigorously promoting industrial green development.

Models (2)–(4) report the threshold effects of technological progress for three types of environmental regulations. Command-and-control environmental regulation and market-incentive environmental regulation have an upward jump after crossing the threshold value. In other words, when the level of technological progress changes from low to high, the promotion effect of environmental regulation on industrial green development is enhanced, but the reasons for the improvement of the two effects are not completely consistent. Among them, the command-and-control environmental regulation restrains the enterprises' pollution emissions by issuing punitive and preventive regulation, which leads to an excessive cost burden placed on enterprises and limits technological progress and industrial green development. Only when the level of technological progress is raised to a certain level can environmental regulation promote the green production process of enterprises and thus improve the quality of production and industrial green development (Shen et al., 2018).

Market-incentive environmental regulation is, to the contrary, more flexible, and industrial enterprises have greater autonomy of choose. When the level of technological progress is low, the cost of pollution emission can be compensated by market means such as subsidies and deposit-return systems, so as to promote industrial green development. At higher levels of technological progress, high-tech enterprises profit from environmental regulation policies through the emissions trading market, and small- and medium-sized enterprises (SMEs) can also imitate and learn green technology processes at a lower cost, speeding up the green development of the entire industry (Wang and Xu, 2015). It is noteworthy that public-participation environmental regulation plays a significant facilitating role only when technological progress is in the low threshold range, and its effect becomes less significant as technological progress increases. One possible reason is that in the low-tech stage, the pollution emissions of enterprises are relatively greater, causing certain damage to the life safety of surrounding residents. At this stage, the polluting behavior of enterprises is more likely to be detected by the public, and they will get punished. Therefore, public-participation environmental regulation has a significantly positive effect on industrial green development. With the continuous advancement of technology, the total amount of pollution emissions decreases, and the harm to the public is alleviated. Thus, the role of public participation in environmental supervision gradually decreases at this time.

Threshold effect of fiscal decentralization

Table 7 displays the results of the fiscal decentralization threshold effect for each variable. In terms of the environmental regulation index, it has only a single fiscal decentralization threshold with a threshold value of 0.1017.[1] From the three types of environmental regulation, the single threshold of fiscal decentralization exists for command-and-control environmental regulation, market-incentive environmental regulation, and public-participation environmental regulation. All have a threshold value of 0.1017, but none of them pass the double threshold test. It can be seen that the threshold value of fiscal decentralization is the same for both the environmental regulation index and different types of environmental regulation, indicating that various environmental regulation instruments reflect fiscal decentralization to a similar extent.

We further conduct a threshold model regression on the single threshold of fiscal decentralization, and the results are in Table 8. Model (1) in the table reports the fiscal decentralization threshold effect of the environmental regulation index. When the level of fiscal decentralization is below the threshold, the promotion effect of environmental regulation on industrial green development is not significant. After the fiscal decentralization crosses the threshold value, environmental regulation significantly promotes industrial green development. At this point, a 1% increase in the environmental regulation index raises the level of industrial green development by 0.0855%. This is because the expansion of fiscal decentralization helps to improve public sector efficiency and promotes government attention to environmental governance issues, which in turn increase green total factor productivity (Adam et al., 2014; Ma et al., 2021; Shi et al., 2022). When the level of fiscal decentralization is low, local governments have less autonomy to promote industrial green development through proactive environmental management. Conversely, when the level of fiscal decentralization rises to a certain level, local governments are able to improve the efficiency of environmental regulation tools based on their own information advantages to stimulate the introduction of technology and green development of enterprises.

Models (2)–(4) show the threshold effects of fiscal decentralization for three types of environmental regulations. Similar to the technological progress threshold, command-and-control environmental regulation and market-incentive environmental regulation jump upward after crossing the threshold - that is, as the degree of fiscal decentralization increases from the low threshold range to the high threshold range, the role of environmental regulation in promoting industrial green development is enhanced. This indicates that fiscal decentralization influences both command-and-control environmental regulation with technical coercion and market-incentive environmental regulation with market flexibility. Appropriate fiscal decentralization effectively mobilizes the enthusiasm of local governments and provides more innovations in public services, which guarantee the smooth implementation of environmental regulations and improve the quality of industrial green development.

The role of public-participation environmental regulation by contrast is not significant at lower levels of fiscal decentralization and only exerts a significant positive effect in the high fiscal decentralization threshold interval. The reason may be that when the degree of fiscal decentralization is low, the local government lacks enthusiasm and initiative and ignores the local public-participation environmental regulation. As a result, the environmental problems as reflected by the public cannot be solved in time, and the role of environmental regulation is not obvious. As the degree of decentralization increases, local governments have certain discretionary power, and the public has more opportunities to directly participate in local governments' decisions on key environmental projects, so as to better take a positive role of environmental regulation on industrial green development.

Analysis of spatial effects

Too strict environmental regulation may restrict economic development, while too loose environmental regulation may turn the local area into a polluting paradise. Therefore, when local governments formulate and implement environmental regulation policies, there is often strategic interaction between regions (Zhang, 2016), which makes the impact of environmental regulation have a spatial effect. This study further incorporates spatial factors into the empirical analysis framework and uses a spatial panel model to focus on the spatial effects of heterogeneous environmental regulations on industrial green development.

Spatial autocorrelation test

Before conducting the spatial model regression, the spatial correlation of variables needs to be examined. Table 9 reports

1 Due to the logarithmic processing of fiscal decentralization, its level has a negative value, but it does not affect the conclusions of the empirical analysis.

TABLE 7 Test of the threshold effect of fiscal decentralization.

Variable	Threshold type	Threshold value	*F*-value	*P*-value	95% confidence interval
ln *ER*	Single	0.1017	22.42	0.0200	[0.0877, 0.1091]
	Double	−0.4200	13.06	0.3340	[−0.4512, −0.4159]
ln *ERC*	Single	0.1017	27.21	0.0120	[0.0877, 0.1091]
	Double	−0.4200	11.87	0.2970	[−0.4512, −0.4159]
ln *ERM*	Single	0.1017	28.17	0.0010	[0.0926, 0.1091]
	Double	−0.2443	6.50	0.7660	[−0.2657, −0.2310]
ln *ERP*	Single	0.1017	23.75	0.0190	[0.0877, 0.1091]
	Double	−0.4200	12.85	0.2450	[−0.4463, −0.4159]

TABLE 8 Regression results of the fiscal decentralization threshold model.

Variable		Threshold variable: fiscal decentralization			
		(1)	(2)	(3)	(4)
ln *ER*	ln *FD* < 0.1017	0.0110 (0.0392)			
	ln *FD* > 0.1017	0.0855** (0.0379)			
ln *ERC*	ln *FD* < 0.1017		0.0757* (0.0404)		
	ln *FD* > 0.1017		0.1405*** (0.0440)		
ln *ERM*	ln *FD* < 0.1017			0.2592*** (0.0599)	
	ln *FD* > 0.1017			0.3307*** (0.0681)	
ln *ERP*	ln *FD* < 0.1017				−0.0064 (0.0506)
	ln *FD* > 0.1017				0.1274*** (0.0364)
Control Variable		Yes	Yes	Yes	Yes
Constant		−7.5318 (5.2398)	−7.4321 (5.1863)	−8.0208 (4.8197)	−7.7482 (5.0670)
N		390	390	390	390
R^2		0.3446	0.3546	0.3683	0.3488

***, **, and * Represent significance at the 1, 5 and 10% levels, respectively. The value in ( ) is the standard error.

TABLE 9 Univariate *Moran's I* index of the industrial green development level.

Year	*Moran's I*	*Z*-value	*P*-value	Year	*Moran's I*	*Z*-value	*P*-value
2006	0.318	2.874	0.002	2013	0.486	4.278	0.000
2007	0.394	3.624	0.000	2014	0.533	4.608	0.000
2008	0.330	3.111	0.001	2015	0.587	4.962	0.000
2009	0.191	1.887	0.030	2016	0.417	3.667	0.000
2010	0.224	2.189	0.014	2017	0.307	2.838	0.002
2011	0.064	0.866	0.193	2018	0.111	1.169	0.121
2012	0.364	3.350	0.000				

the results of the global *Moran's I* index test for the level of industrial green development. The results in the table show that the univariate *Moran's I* index of industrial green development is positive and passes the 5% significance test except for 2011 and 2018. Overall, the level of industrial green development in China has a strong positive spatial correlation, and industrial green development among adjacent provinces presents an obvious spatial clustering and dependence characteristics.

Since this part explores the spatial influence of environmental regulation on industrial green development, it is necessary to further investigate the spatial correlation between the two – that is, to measure the bivariate global *Moran's I* index. Figure 1 portrays the bivariate *Moran's I* index of environmental regulation and industrial green development. As a whole, *Moran's I* index for different environmental regulation indicators and its index for industrial green development are positive and significant. Although the spatial correlation between environmental regulation and industrial green development fluctuates in different years, it does not change the positive spatial correlation between them. In conclusion, both univariate and bivariate global *Moran's I* indices indicate that environmental regulation and industrial green development are

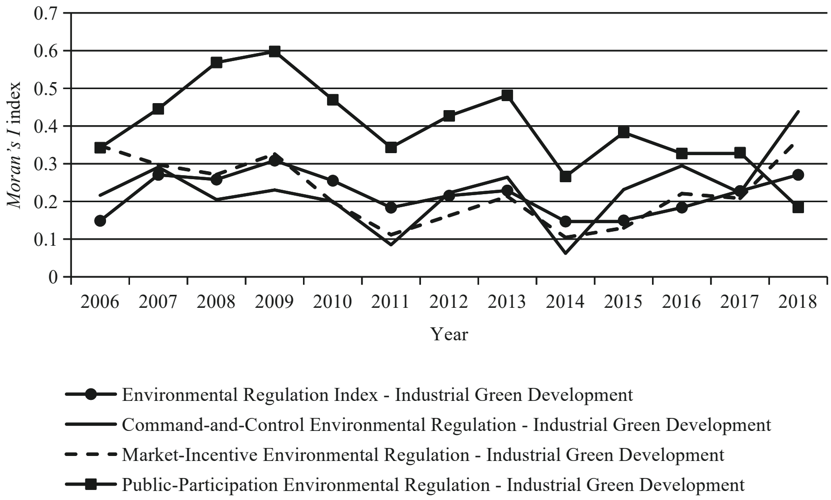

FIGURE 1
Bivariate *Moran's I* index of heterogeneous environmental regulation and industrial green development.

influenced by spatial factors. Therefore, it is necessary to use spatial econometric methods for an in-depth discussion.

Selection and regression of spatial econometric model

Before model estimation, the spatial econometric model needs to be identified and tested, and Table 10 lists the results. On the one hand, the LM test is used to explore whether a SAR or a SEM should be selected. From the results of the LM test and the robust LM test, the null hypothesis of no spatial lag or spatial error is rejected at the 1% level for the environmental regulation index and the three types of environmental regulation instruments, meaning that a spatial model needs to be selected for regression. On the other hand, we also examine which spatial model should be chosen specifically. Both the LR test and the Wald test pass the 1% significance test, indicating that SDM cannot be simplified into SAR or SEM. In addition, the Hausman test results both reject the null hypothesis of using random effects. Therefore, we choose the fixed-effect SDM to explore the spatial effect of heterogeneous environmental regulations on industrial green development.

Table 11 shows the regression results of SDM. In terms of the lagged term spatial coefficient (rho), the estimated coefficients of the environmental regulation index and three types of environmental regulation are all significant at the 10% level, suggesting a strong spatial spillover effect of industrial green development, which again confirms the conclusion drawn from the spatial correlation test. In terms of the main effect of environmental regulation, the estimated coefficients of the environmental regulation index and the three types of environmental regulations are all smaller than the coefficient values when spatial factors are not considered, representing that the promotion of environmental regulation is affected by the combined force of environmental regulation in the entire region. The actual effect of environmental regulation does not fully meet the expectation due to the superposition of many influencing factors, such as inter-regional environmental regulation strategy interaction and spatial clustering of industrial green development. Hence, the use of environmental regulation instruments should be scientifically combined from the regional level rather than limited to the local area. At the same time, the coefficients of environmental regulation index, market-incentive environmental regulation, and public-participation environmental regulation are significantly positive after considering the spatial factor, while the coefficient of command-and-control environmental regulation does not pass the significance level test, which proves that there may be competition to the bottom in the formulation of environmental regulation policies by local governments in order to develop the regional economy, leading to the failure of environmental regulation.

To examine the marginal effects of heterogeneous environmental regulations on industrial green development, the spatial effects need to be decomposed, and the results are reported in Table 12. The three effect coefficients of environmental regulation index, market-incentive environmental regulation, and public-participation environmental regulation are significantly positive, and the indirect and total effects of command-and-control environmental regulation are significantly positive, while the direct effect is not significant. This means that market-incentive environmental regulation and public-participation environmental regulation are beneficial to industrial green development of local and neighboring provinces, while command-and-control environmental regulation mainly is manifested in promoting industrial green development in

TABLE 10 Identification test of the spatial model.

Content		ln *ER*		ln *ERC*		ln *ERM*		ln *ERP*	
		χ^2	*P*-value	χ^2	*P*-value	χ^2	*P*-value	χ^2	*P*-value
Test of SEM and SLM	LM-lag	94.586	0.000	90.091	0.000	90.650	0.000	73.599	0.000
	R-LM-lag	22.144	0.000	22.955	0.000	22.646	0.000	12.702	0.000
	LM-error	79.266	0.000	72.331	0.000	73.019	0.000	72.692	0.000
	R-LM-error	6.823	0.009	5.195	0.023	5.014	0.025	11.794	0.001
Simplified test for SDM	LR-lag	35.46	0.000	41.51	0.000	33.15	0.000	39.45	0.000
	Wald-lag	36.76	0.000	43.13	0.000	34.39	0.000	40.98	0.000
	LR-error	38.22	0.000	44.97	0.000	38.97	0.000	42.46	0.000
	Wald-error	35.02	0.000	40.15	0.000	36.01	0.000	39.54	0.000
Hausman		29.01	0.0344	28.31	0.0414	41.55	0.0008	29.24	0.0324

TABLE 11 The results of the spatial Durbin model.

Variable	(1)	(2)	(3)	(4)
ln *ER*	0.0614** (0.0279)			
ln *ERC*		0.0030 (0.0385)		
ln *ERM*			0.1596** (0.0653)	
ln *ERP*				0.0906** (0.0317)
W * ln *ER*	0.0793* (0.0476)			
W * ln *ERC*		0.1989*** (0.0626)		
W * ln *ERM*			0.1421 (0.0991)	
W * ln *ERP*				0.1206** (0.0534)
Control variable	Yes	Yes	Yes	Yes
Rho	0.4622*** (0.0511)	0.4365*** (0.0532)	0.4678*** (0.0503)	0.4493*** (0.0518)
sigma2_e	0.1194*** (0.0087)	0.1192*** (0.0086)	0.1176*** (0.0085)	0.1184*** (0.0086)
Log-likelihood	−150.2593	−148.6266	−147.5437	−147.9745
Observations	390	390	390	390
R^2	0.3899	0.4108	0.3823	0.4087

***, **, and * Represent significance at the 1, 5, and 10% levels, respectively. The value in ( ) is the standard error. sigma2_e is the within-group standard deviation.

TABLE 12 Decomposition results of spatial effects.

Variable	Direct effect	Indirect effect	Total effect
ln *ER*	0.0781** (0.0307)	0.1945** (0.0825)	0.2726*** (0.0993)
ln *ERC*	0.0307 (0.0399)	0.3394*** (0.0932)	0.3701*** (0.1066)
ln *ERM*	0.1943*** (0.0668)	0.3965** (0.1584)	0.5908*** (0.1765)
ln *ERP*	0.1141*** (0.0352)	0.2814*** (0.0920)	0.3955*** (0.1131)
Control variable	Yes	Yes	Yes
Fixed effect	Yes	Yes	Yes

***, **, and * Represent significance at the 1, 5, and 10% levels, respectively. The value in ( ) is the standard error.

neighboring provinces. In recent years, with the gradual improvement of an environmental performance assessment system, inter-provincial environmental regulation competition behavior has improved and formed a “ruler effect” (Zhang et al., 2010). As a result, the environmental regulations in adjacent areas have a certain similarity, and the increase in the intensity of environmental regulation in one place will inevitably lead to the corresponding adjustment of environmental regulations in adjacent areas, thereby driving industry’s green development. The direct effect of command-and-control environmental regulation is not significant, which also indicates that the current environmental regulation tools characterized by government coercion measures are not effective means to promote industrial green development. It is often better to make full use of diversified tools such as market-incentive environmental regulation and public-participation environmental regulation.

Conclusion and policy recommendations

In the context of the increasingly severe industrial pollution problem, this study aims to explore the relationship between environmental regulation and industrial green development, to provide a theoretical basis for further identifying the effectiveness of environmental regulation, and to make up for the lack of research on industrial green development, so as to find a sustainable development path that balances industrial development and environmental protection.

Therefore, based on panel data of 30 provinces in China from 2006 to 2018, this study constructs a panel threshold model to empirically test the nonlinear characteristics of different types of environmental regulations on industrial green development from the perspective of technological progress and fiscal decentralization. We further use the spatial panel model to analyze the spatial effects of different environmental regulations on industrial green development. The main conclusions of this study are as follows: (1) The environmental regulation index has a significant role in promoting industrial green development. For every 1% increase in the intensity of environmental regulation, the level of industrial green development rises by at least 0.0840%. (2) Environmental regulation index, command-and-control environmental regulation, market-incentive environmental regulation, and public-participation environmental regulation all have only a single threshold of technological progress and fiscal decentralization. (3) There is a significantly positive spatial correlation between different environmental regulation indicators and industrial green development. (4) The results of spatial effect analysis show that, except for command-and-control environmental regulation, the environmental regulation index and the other two types of environmental regulation have significantly positive impacts on industrial green development.

Based on the above research conclusions, we propose the following policy recommendations: (1) Since different types of environmental regulations have different impacts on industrial green development, it is necessary to use heterogeneous environmental regulation tools flexibly. For enterprises with serious industrial pollution, local governments should mainly adopt command-and-control environmental regulations and strictly supervise the pollution discharge behavior of enterprises. At the same time, the government needs to fully stimulate the vitality of market-incentive environmental regulation such as carbon emissions trading and constantly improve their trading market and systems. It should build a channel for public participation in environmental regulation and expand the coverage of education and publicity. (2) When technological progress crosses the threshold, the positive role of environmental regulation in promoting industrial green development is greatly enhanced, which means that local governments should further improve the technological innovation capabilities of industrial enterprises. The government must encourage industrial enterprises to step up R&D of clean technologies through tax incentives and financial subsidies and introduce foreign advanced environmental protection technologies to promote the upgrading of industrial enterprises. In addition, great importance must be attached to the patent protection of clean technology innovation and process efficiency improvement, providing institutional guarantee for enterprises to carry out technological R&D activities. (3) Since fiscal decentralization plays an important role in the process of environmental regulation promoting green industrial development, it is necessary to appropriately decentralize the government's environmental governance power. The central government should further expand the authority of such departments in personnel arrangement and use of environmental governance funds to ensure the smooth implementation of environmental management power. At the same time, the proportion of environmental governance in the assessment of local governments must be strengthened, so as to encourage local governments to focus on improving environmental issues. (4) The spatial dependence of environmental problems should not be ignored, and the government needs to pay attention to the joint prevention and control of regional pollution. Local governments should improve the inter-regional cooperation mechanisms and establish regional sharing models of green technologies to jointly promote the coordinated management of environmental pollution.

Limitations and future research directions

Although we have expanded the related research from both theoretical and practical aspects, there are still the following shortcomings. First, our research focuses on provincial administrative units and fails to cover data on prefecture-level cities and enterprises. Subsequent research should further analyze the data of prefecture-level cities or enterprises, and conduct detailed research according to the industrial layout of urban agglomerations and the nature of enterprises. Second, this study lacks an examination of different types of industries. Future research should divide specific industries and further investigate the role of factor allocation ratios between different industries in the impact of environmental regulation on industrial green development. Third, we only test the influence of technological progress and fiscal decentralization, while the green development effect of environmental regulation may also be affected by other factors, especially the role of government behavior and its results. Subsequent research should be expanded from other perspectives such as government competition, market segmentation, and factor distortion.

Data availability statement

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

Author contributions

YY and HC: conceptualization and writing–original draft preparation, review and editing. HC: methodology, project administration, funding acquisition, and formal analysis. YY: software and resources. HC, YY, and HH: validation and data curation. MY: investigation. YY and HH: visualization. HH: supervision. 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.

Publisher's note

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