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Research article

Heterogeneous relations among environmental regulation, technological innovation, and environmental pollution

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ABSTRACT

In this study, interprovincial panel data of China from 2011 to 2020 are selected and empirically examined to determine the effects of three types of environmental regulation tools: command-and-control, market-incentive, and public-participation types. Then, hierarchical regression analysis and instrumental variables are used to analyze and verify the mediating role of technological innovation. Results show no significant relationship between command-and-control regulation and environmental pollution, while market-incentive and public-participation regulations have a significantly negative inhibitory effect on environmental pollution and contribute to pollution reduction. In addition, product and process innovations play partially mediating roles between market-incentive regulation and environmental pollution and between public-participation regulation and environmental pollution, respectively, thus indicating that technological innovation is an effective way to reduce pollutant emissions. Compared with product innovation, process innovation has a better effect on pollution emission reduction but a smaller incentive effect under environmental regulation. This finding indicates that enterprise technology innovation and environmental regulation fail to achieve a suitable match for maximizing environmental benefits. Further analysis shows that the effects of the three types of environmental regulation tools on reducing pollution emissions vary in different periods and show significant changes around 2010. The effects of command-based regulation weaken, while those of the pollution abatement of market-incentive and public-participation regulations increase.

1. Introduction

According to the 2022 Global Environmental Performance Index (EPI) Report (content from website: https://envirocenter.yale.edu/) jointly released by Yale University, Columbia University, and other research units, China ranks 160th of 180 countries with the lowest score of 28.4 in 10 years in terms of environmental health policy objectives and ecosystem. This ranking shows that China's environmental performance still has a large gap compared with other countries and regions. At the same time, according to the 2022 Annual Communiqué on the State of China's Ecological Environment released by the Chinese Ministry of Ecology and Environment, 126 cities in China, accounting for 37.16%, fall below the exceeds standards grade for air quality, and 199 centralized domestic drinking water sources require water quality monitoring (content from website: https://www.mee.gov.cn/). In addition, soil pollution from heavy metals and cadmium has not been effectively alleviated, which shows that the environmental pollution problem is also a

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serious threat to the daily lives and health of residents. Therefore, curbing pollutant emissions effectively and improving the quality of the ecological and human living environment have become focal issues of concern for the academia, the government, and the public in recent years because of their social and practical significance.

Environmental regulation refers to regulating and restricting behaviors that pollute the public environment. The Chinese government has established a comprehensive system of environmental regulation policies to improve environmental conditions. Under such policies, the emission behavior of enterprises and other pollution-emitting organizations will be strictly monitored and restricted to reduce pollutant emissions. However, do these policies truly reduce emissions? Scholars have diverse opinions on this issue. Most scholars believe that the relevant policies have helped to inhibit pollution emissions. For instance, Zhang et al. (2018) pointed out that the Chinese government's key monitoring policy on water pollution emissions has played a significant role [1], thus confirming the effectiveness of environmental regulation. However, some scholars hold the opposite view that environmental regulation policies still have room for improvement. Jin and Lin (2014) asserted that governmental environmental regulation policies cannot always reduce emissions; for example, most environmental regulation tools can reduce emissions of only one type of pollutant, and the effect on other pollutants is insignificant [2]. In addition, Xu et al. (2014) argued that environmental regulation can constrain corporate behavior and may not substantially impact pollution emissions; moreover, environmental regulation is costly and unsustainable [3]. Meanwhile, Hering and Poncet (2014) revealed that environmental regulation policies have a dampening effect on air pollutant emissions and impede the development of foreign trade [4].

As a result, scholars have begun to explore the reasons for the divergence in research. The relevant literature has two types of mainstream views. The first category is that policy tools for environmental regulation have different modes of action and intensity, thus having various impacts on polluters' behavior. Command and market types are the first two policy tools. The command type emphasizes the direct intervention of the government and gives punitive measures, such as closure and large fines to illegal dischargers, which can achieve significant results in the short term [5]. However, the cost of governance is high and unsustainable. Market-based policy instruments focus on aggregate control and allow the trading of emission rights, which are slow to achieve policy effects but effective in the long term [6]. China's policy practice, along with the depth of the policy, has also developed the information-incentive type, the public-participation type, and other objective types of policy tools to promote the progress such practice. Given the multiple stages of economic development in various regions, differences in the performance of production factors, such as technology, economy, and manpower, affect the concern and participation of the government, enterprises, and residents in environmental issues; thus, different environmental policy tools have exhibited mixed pollution control effects in different regions [7]. Kemp (1995) argued that on the basis of endowment conditions, such as the local industrial structure and the level of economic development, governmental departments should opt for environmental regulation policy tools as the best way to control pollution. The selection of such tools is the key to enhancing the policy's effectiveness. This need for selection confirms that these instruments lead to differences in policy effects [8].

The second category is that technological innovation behaviors of discharging enterprises lead to differences in policy effects. The relationship between environmental regulation and technological innovation has been a key research topic since ancient times. The classic hypotheses explaining the relationship between the two are "compliance cost" and "innovation compensation." Wilcoxen (1990) stated that the compliance cost view explains that under the environmental regulation policy, the technological innovation capacity of enterprises is weakened, and the cost of pollution control has a crowding-out effect on the innovation capital [9]. Barbera and Mcconnell (1990) expressed that the view of innovation compensation means that under environmental regulation, the innovation motivation of enterprises is strengthened, and such enterprises are incentivized to achieve pollution control through technological innovation [10]. As a result, under the environmental regulation policy tool, enterprises can compensate for the cost of pollution control by enhancing their revenues without taking pollution mitigation measures to minimize the impact of the policy on the enterprises [11]. At this time, the effect of pollution control is challenging to demonstrate. Enterprises can also implement process innovation to reduce the cost of pollution control to respond to the environmental regulatory policy [12]. Chang-Ping and Min-Jie (2016) showed that various modes of technological innovation lead to different pollution control effects [13]. The influence of technological innovation on the variations in the pollution control effects of environmental regulatory policies is confirmed indirectly.

Environmental regulation and technological innovation may be responsible for differences in the effectiveness of pollution control. Different types of environmental regulation tools have varying degrees of impact on the cost of pollution control because of their characteristics. In addition, the two types of technological innovation modes provide enterprises with several ways to cope, which directly determines the scale of their emissions. Thus, this study considers whether the above research implies a coupling relationship between different types of environmental regulation and technological innovation modes and their joint impact on the pollution control effect of environmental regulation policies. Notably, no relevant article has been able to solve this issue. Hence, the present study intends to conduct cross-border and integration research to address the above shortcomings. Specifically, an explanatory framework for the pollution control effects of environmental regulatory policies is constructed on the basis of three types of environmental regulatory instruments and two types of innovation models. Furthermore, the study proposes relevant research hypotheses and tests the above inferences using panel data from 30 Chinese cities. This study examines the fitness relationship between the types of policy instruments and technological innovation models. It addresses the question, "What type of environmental regulation policy instrument matches with the innovation mode of enterprises to minimize pollution emissions?"

This work constructs a novel perspective to explain the above research differences and provides new guidance for policy and enterprise managers to understand the strategy. At the same time, this study constructs a macro–micro integration model, which is rarely seen in existing research, to provide a new vision for the research system of environmental regulation policy and promote the in-depth development of this research field. The special contribution of the study is that it can provide concrete suggestions for China's practical implementations of the environmental regulation policy rather than generalized and abstract conclusions.

2. Literature review

2.1. Environmental pollution and its regulation

Comprehensive domestic and foreign literature has focused on the relationship between environmental pollution and regulation. However, the findings have been inconsistent and varied depending on the research background, measurement methods, and sample selection. The pertinent concepts in the relevant research can be divided into two main types. First, environmental regulations effectively inhibit pollution emissions [14]. Researchers believe that tightening environmental regulations may increase the production costs of enterprises and even negatively affect their survival and development. Given the pressure from multiple aspects, enterprises can reduce the emission of pollutants, which is conducive to the alleviation of regional environmental pollution problems. Second, although most of the literature indicates that environmental regulation can significantly improve environmental quality, other studies have put forward different views. For example, command-and-control regulatory instruments are too rigid and easily lead to insufficient space and motivation for firms to respond, which is not conducive to promoting pollution reduction [15] and improving environmental quality [16]. Furthermore, the effects of environmental regulations vary by region and can cause diametrically opposed results [17]. Thus, the relationship between environmental regulations and environmental pollution cannot be generalized.

In response to the above different results, scholars in China have focused on explaining the reasons from different perspectives, thus gradually forming a new research strand that highlights the heterogeneity of the relationship between environmental regulation and environmental pollution. Li and Zhang(2019) analyzed the role of environmental decentralization on the relationship between environmental regulation and industrial pollution management efficiency using the Tobit model; their results revealed that a high autonomy of local governments in environmental governance is conducive to the proper implementation of environmental regulations [18]. Qiu Shilai et al. (2018) found that differences in environmental regulation approaches and in the intensity of regulation can lead to varying relationships between environmental regulation and performance [19]. In addition, Zeng Qian et al. (2020) explained that the industrial structures in each region are the reason for the variations in the regulatory effects; command-based regulation gradually decreases as the industrial structure advances, while the effects of information disclosure and public participation-based regulation are enhanced [20].

2.2. Environmental regulation and technological innovation

Given the key role of technological progress in promoting the harmonious development of the economy and the environment, the relationship with technological innovation has become another important element of environmental regulation research. Traditional neoclassical economics believes that tightening environmental regulations increases the production cost of enterprises and their economic burden; this scenario can lead enterprises to invest the funds originally used for innovation in pollution control and emission reduction, thereby undermining their incentive and ability to innovate [21], which is called the "compliance cost hypothesis." This view prevailed for a long time until the Porter hypothesis was proposed, arguing that technological innovation under environmental regulation helps firms to compensate for the cost of environmental compliance and that reasonable environmental regulation has an incentive effect on firms' technological innovation [22]. Rennings (2000) identified dual externalities and regulatory push/pull as the two main characteristics of technological innovation under environmental regulation [23]. Horbach, Rammer, and Rennings (2012) empirically tested the decisive effect of the push/pull of environmental regulation on green technological innovation [24]. The above classical studies laid the foundation for the subsequent research.

Numerous domestic scholars have examined the applicability of the Porter hypothesis in China on the basis of the country's objective reality, thus forming three main views. First, the Porter hypothesis is valid because of the incentive effect of environmental regulation. Using interprovincial data in China, Lele and Zhao Jun (2018) analyzed the relationship between environmental regulation and technological innovation through a panel threshold model; their results showed that high-intensity environmental regulation forces firms to engage in technological innovation [25]. In addition, Sihui Li and Baochang Xu (2020) measured the intensity of environmental regulation by constructing a linear weighted composite index and conducting an empirical analysis; they revealed that overall environmental regulation has a significant effect [26]. The second view focuses on the relationship between environmental regulation and technological innovation, which is nonlinear; the impact of environmental regulation on technological innovation has a threshold. L Huang and Z Lei (2021) empirically analyzed the effect of three types of environmental regulation on corporate green investment using data of Chinese listed companies from 2008 to 2016; their findings indicated an inverted U-shaped relationship between command-and-control environmental regulation and corporate green investment [27]. Fan, Dan, and Sun (2020) showed a threshold effect between market-incentive regulation and green technology innovation; the relationship between them gradually becomes nonlinear after crossing the inflection point [28]. Third, the relationship between environmental regulation and technological innovation is influenced by other factors and uncertainty. Mao Jianhui (2019) indicated that regional heterogeneity may explain the divergent results of the validation of the Porter hypothesis; their empirical results showed that the incentive effect of environmental regulation on technological innovation holds in the eastern region of China but does not hold or even has the opposite outcome in the western region [29]. Wang Zhenyu et al. (2020) examined the heterogeneity of the technological innovation effect at the micro level; they found that the types of patent, firm ownership, and industry affect the relationship between environmental regulation and technological innovation [30].

The existing literature has focused on the relationship among environmental regulation, technological innovation, and environmental pollution. Although this combination is the key to revealing the role of environmental regulation in pollution reduction, few studies have analyzed all three in the same theoretical framework. This research gap is not conducive to enhancing the policy effects of environmental regulations and deepening the management of environmental regulations. To address the above shortcomings, this study proposes the following extensions. First, it seeks to construct a theoretical model involving "environmental regulation–technology innovation–environmental pollution" on the basis of the three-stage model of "change–implementation–impact." Second, this study classifies environmental regulation into command-and-control, market-incentive, and public-participation types. We further subdivide technological innovation into product and process on the basis of the abovementioned three classifications of environmental regulation. Third, the variables and data are used to measure technological innovation by using expenditures rather than patent data to avoid the influence of undesirable phenomena as "quantity-only," symbolic, and political innovation on the research results. This study aims to expand the relevant theoretical research and provide useful reference for the policy formulation and optimization of environmental regulation and the improvement of environmental quality.

3. Theoretical foundation and research hypothesis

3.1. Theoretical basis

In pursuing economic development, we cannot neglect environment protection, ecosystem production, and renewal capacity. Preventing damage to the environment to meet future human needs and its upper limit is the common viewpoint of sustainable development and green development system theories. This view is also the primary premise to achieve the harmonious coexistence between human and nature. However, the environment and the resources that can be obtained from it have typical properties of public goods, and pollution emissions have negative externality characteristics. Hence, the market alone cannot reduce emissions on a large scale. The government needs to intervene by using administrative, economic, and public monitoring means to overcome the market mechanism and maximize the interests of most social actors with insufficient incentive to reduce emissions. Thus, this scenario of environmental regulation was born. In this context, environmental regulation has emerged and evolved in various ways and means. At the same time, the actual situation of Chinese enterprises indicate that technological innovation plays an important role in reducing pollution through environmental regulations. Moreover, its ability to help enterprises establish costs first and then improve technological and product advantages is becoming increasingly apparent. Therefore, on the basis of externality and technological innovation theories, the chain of influence of environmental regulation and technological innovation on environmental pollution can be constructed.

3.2. Definition of variables

The concepts in this study involve three levels of environmental regulation policy, enterprise response behavior, and policy implementation results, which build up a chain of influence on environmental regulation policy. Environmental regulatory policies refer to a series of policies and initiatives implemented by government departments to protect the environment and constrain public environmental pollution behavior, including command-and-control, market-incentive, and public-participation policy tools. These three types of policy tools are generated in China's environmental regulation policy practice with a practical basis. At the same time, the three categorizations of environmental regulation policy tools are consistent with the existing literature. The specific connotations of environmental regulation policy and its tools align with those described in Section I.

This study refers to technological innovation as a series of innovative activities by emitting enterprises to achieve emission standards or cost offsets under environmental regulation policies [31]. Technological innovation has always been a focal point in environmental regulation research. On the one hand, enterprises can improve production processes and enhance resource utilization efficiency to cope with environmental pollution emission inspection, which can then reduce the content of pollutants in emissions [32]. On the other hand, to ensure that the daily operation of the enterprise is not affected by the intensification of environmental regulation, the enterprise is likely to change the product line or look for a new source of profit to realize the transformation to enter the low-emission industry [33]. This process also needs to be realized through technological innovation. Thus, technological innovation can be further subdivided into production process innovation and product innovation under the environmental regulation policy, thus reflecting the two forms of enterprises' response to environmental regulation from the end of emission and the production source, respectively. Various responses imply different emission effects; hence, the type of innovation behavior of enterprises in environmental regulation affects government policymaking [34]. When a difference in the type of corporate innovation is observed, the approach toward environmental regulation policy and its trajectory are also different. As such, the present study will further differentiate between firms' technological innovation styles. Process innovation refers to the technological updating and application of production processes and the techniques that enterprises make to improve resource utilization efficiency, reduce pollutant generation, and purify emissions. Product innovation refers to the innovation and efforts made by enterprises in developing new products and opening new market channels. The results are generally products or services that align with market demand rather than technological progress.

Environmental pollution, as the explanatory variable of interest in this study, is defined using the direct description method. The primary purpose of environmental regulation is to reduce the emissions of the production process of enterprises. Thus, this work refers to environmental pollution as the production process of enterprises to emit waste, which explicitly includes waste gas, wastewater, and solid waste. Some examples are the emission of sulfur dioxide, other harmful gases, toxic liquids containing phosphorus, and solids such as mining waste. Environmental regulation aims to compel, incentivize, and guide enterprises to emit goods containing as few hazardous substances as possible. Therefore, using the above concepts to define them is appropriate. In summary, the study constructs a set of variables, including environmental regulation, environmental pollution, and technological innovation, which can be used in subsequent empirical studies.

3.3. Research hypotheses

3.3.1. Relationship between heterogeneous environmental regulation and pollution

As an important policy, environmental regulation serves as the goal to promote the reduction of pollutant emissions and alleviate environmental pollution. The distinction between environmental regulation tools in terms of their regulatory dynamics and realization mechanisms is necessary; therefore, the effects of regulation may also differ when discussing the pollution abatement effects of environmental regulation [35]. Otherwise, the research results may be biased and mislead environmental policymaking and regulatory tool selection. The main characteristics of command-and-control regulatory instruments are mandatory, administrative orders to ensure implementation. Moreover, technical and performance standards are their main regulatory instruments that must be complied with by the regulated parties. Interviews, deadlines for rectification, large fines, shutdowns, and forced withdrawals are the disciplinary tools for noncompliant enterprises. Ouyang, Shao, and Zhu et al. (2018) concluded that enhancing the degree of coercion of environmental regulatory policy instruments and increasing the frequency of direct intervention guarantee the improvement of policy effectiveness [36]. Market-incentive regulation is a tool based on the nature of enterprises' pursuit of profit maximization, which is mainly in the form of environmental taxes, emission fees, and emission trading permits. The regulatory mechanism is the internalization of environmental pollution costs. Sharma, Lal, and Raj (2009) validated the effectiveness of carbon emissions trading as a mainstream market-based regulatory tool and confirmed that guidance based on the market mechanism is another way to realize the objectives of environmental regulatory policy [37]. Finally, enhancing the intensity of information disclosure by the government and enterprises and promoting orderly public participation in environmental regulation are the main elements of policies based on public participation, which play a supervisory role for the subject and supplier of regulation. Peng et al. (2013) confirmed the synergistic effect of environmental regulation and public participation on the transfer of polluting industries using interprovincial panel data in China, thus highlighting the effectiveness of regulatory tools based on public participation [38].

Policies must not only force enterprises to reduce emissions from the demand side but also suppress environmental corruption as a third-party supervisor and ensure the implementation of environmental protection policies.

Specifically, from the perspective of cost internalization, various factors can increase the production costs of enterprises. Some of these factors include investments that may need to meet technical and performance standards under command-and-control regulation, high fines and other expenses when environmental violations occur and are punished, and the emission fees to be paid under market-incentive regulation. These aspects cause enterprises to consider the environmental impact when they discharge pollution. In addition, the combination of the public-participation type of regulatory tools and the nature of enterprises to pursue profit maximization present an incentive to reduce emissions under environmental regulation [39]. As environmental problems become increasingly prominent and relevant regulations are implemented, public consciousness and green consumption tendencies accelerate. This acceleration hinders environmentally harmful products in the future market and provides additional space and support to environmentally friendly companies and products. Rational business managers can foresee this outcome. Given the effect of increased environmental information disclosure, managers can take proactive environmental behavior to maintain their customers and market share, thereby achieving pollution reduction. On this basis, we propose the following research hypotheses.

Hypothesis 1. Strengthening command-and-control environmental regulation is conducive to promoting pollution abatement.

Hypothesis 2. Strengthening market-based environmental regulation is conducive to promoting pollution abatement.

Hypothesis 3. Strengthening public-participation environmental regulation is conducive to promoting pollution abatement.

3.3.2. Intermediary role of technological innovation

According to the nature of enterprises' pursuit of profit maximization, under the influence of heterogeneous environmental regulations, enterprises' motivation to engage in technological innovation comes from the following two points. (1) From the perspective of legality, enterprises can achieve the green transformation of product structure, the reduction of pollutant emission demand, and the improvement of pollutant cleanliness through technological innovation. These actions can help enterprises comply with environmental laws, regulations, and norms, which is one of the conditions for their survival. (2) From the perspective of stakeholders, technological innovation is used to promote environmental protection. Companies can improve and benefit from their environmental protection image by communicating their attitude and determination to consumers, the government, and investors. Ma and Li (2021) identified environmental regulation as one of the driving forces of technological innovation in enterprises and empirically examined the relationship between environmental regulation and technological innovation [40]. At the same time, the possibility that product innovation is affected by environmental regulation has also been verified. Shao et al. (2020) concluded that, through product innovation, enterprises can transition from a high-pollution to a low-pollution emission market, which is beneficial for enterprises to cope with environmental regulation [41]. Specifically, in addition to optimizing product composition and reducing emissions demand, product innovation in heterogeneous environmental regulation is driven by the pursuit of higher revenues and market competitiveness. Successful innovative products often have multiple advantages [42]. Moreover, the benefits of innovation are higher, thus helping firms to cover the costs of environmental compliance effectively. Process innovation is one of the main approaches for the end-of-pipe management of pollutant emissions for firms under heterogeneous regulation.

As for the view that the increased cost of environmental regulations has a crowding-out effect on inputs and hinders technological innovation [43], this study argues that the abovementioned "cost of compliance" essentially weakens the capability and self-confidence of enterprises to innovate but not the incentive. The green consumer market has further grown, intellectual property protection has been continuously promoted, and the government has provided support and subsidies for environmental protection, such as tax incentives and government subsidies; therefore, the disadvantages of high investment, high risk, and long cycle of technological innovation have gradually become diluted [44]. Thus, the burden and concern regarding the technological innovation of enterprises have weakened. By contrast, the motivation to innovate has increased, and the ability to achieve advancement has relatively improved. Moreover, the effect of “compliance cost” is reduced. In summary, we argue that environmental regulation can force enterprises to innovate. On this basis, we propose the following research hypotheses.

Hypothesis 4a. Strengthening command-and-control environmental regulations can stimulate firms’ product innovation.

Hypothesis 4b. Strengthening command-and-control environmental regulations can stimulate firms’ process innovation.

Hypothesis 5a. Strengthening the market-incentive environmental regulation can stimulate firms’ product innovation.

Hypothesis 5b. Strengthening market-incentive environmental regulation can stimulate firms’ process innovation.

Hypothesis 6a. Strengthening public-participation environmental regulation can stimulate firms’ product innovation.

Hypothesis 6b. Strengthening public-participation environmental regulation can stimulate the firms’ process innovation.

Under the current environmental regulation in China, the technological innovation of enterprises to reduce pollutant emissions to achieve environmental compliance is an objective fact, as reflected in academic research. This transmission chain of environmental regulation affecting environmental quality through technological innovation is aligned with the three-stage model of “policy formulation–policy response–policy effect.” Specifically, innovation can be achieved through the production or design of low-emission green products, product innovation that promotes the green transformation of product composition or even enterprises and industries, and the research and development or introduction of process innovation that can directly improve resource utilization efficiency and reduce pollutant emissions at the same output. These processes can all contribute to the improvement of environmental quality. Acemoglu (2012) analyzed and verified the relationship among environmental regulation, technological progress, and environmental quality; their results showed that regulatory policies have an incentive effect on innovation and are conducive to pollution reduction [45]. Zhang Hua and Wei Xiaoping (2014) [46] and Wu Weiping and He Qiao (2017) [47] confirmed the mediating role of technological innovation between environmental regulation and the reduction of carbon and pollution emissions, respectively. The present study diverges from previous studies by further delineating the environmental regulation approach and the technological innovation model. This delineation is conducive to deepening the regulatory management, refining the policy formulation, and seeking breakthrough points for enhancing the regulatory effect. To analyze the specific path through which heterogeneous environmental regulation affects pollution reduction, we propose the following research hypotheses.

Hypothesis 7. Product innovation plays a mediating role between command-and-control regulation and environmental pollution.

Hypothesis 8. Product innovation plays a mediating role between market-incentive regulation and environmental pollution.

Hypothesis 9. Product innovation plays a mediating role between public-participation regulation and environmental pollution.

Hypothesis 10. Process innovation plays a mediating role between command-and-control regulation and environmental pollution.

Hypothesis 11. Process innovation plays a mediating role between market-incentive regulation and environmental pollution.

Hypothesis 12. Process innovation plays a mediating role between public-participation regulation and environmental pollution.

The theoretical model is shown in Fig. 1.

3.4. Econometric model setting

Given the above theoretical analysis and hypotheses, this study constructs the econometric model shown in Eqs. (1) and (3) to (5) to verify the pollution reduction effect of heterogeneous environmental regulations and the mediating role of technological innovation. At the same time, we test whether a nonlinear relationship exists among environmental regulations, environmental pollution, and technological innovation by introducing its squared term to constitute the model shown in the equations. The specific model is set as follows:

$$EQ_{it} = \beta_0 + \beta_1 ER_{it} + \beta_2 X_{it} + \varepsilon_{it} \tag{1}$$

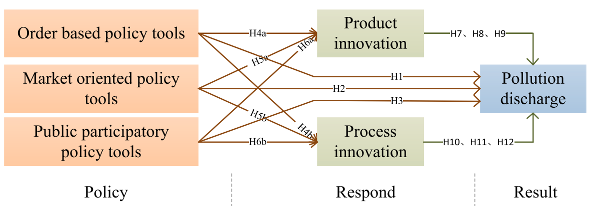

Fig. 1. Theoretical model.

$$EQ_{it} = \beta_0 + \beta_1 ER_{it} + \beta_2 X_{it} + \beta_3 {X_{it}}^2 + \varepsilon_{it} \tag{2}$$

$$TI_{it} = \beta_0 + \beta_1 ER_{it} + \beta_2 X_{it} + \varepsilon_{it} \tag{3}$$

$$TI_{it} = \beta_0 + \beta_1 ER_{it} + \beta_2 X_{it} + \beta_3 {X_{it}}^2 + \varepsilon_{it} \tag{4}$$

$$EQ_{it} = \beta_0 + \beta_1 ER_{it} + \beta_2 TI_{it} + \beta_3 X_{it} + \varepsilon_{it} \tag{5}$$

where i and t denote provinces and years, respectively. β is the regression coefficient of each variable. EQit denotes the environmental pollution emission status of each province. ERit denotes environmental regulation, which is divided into three categories: command-and-control (ORDER), market-incentive (MRKT), and public participation (PUBPA). TIit denotes technological innovation, which is further divided into product innovation (PINN) and process. Xit is the control variable, including the degree of foreign openness (FDI), level of economic development (EMC), industrial structure (ISTR), and the regional dummy variable (RGN), thus representing the random disturbance term.

3.5. Variable selection and data sources

3.5.1. Explained variable

This study uses environmental pollution as the explained variable, which refers to the annual pollutant emission status of each province. Given that many factors affecting environmental quality and pollutant types are not unique, fully reflecting the status of environmental pollution is difficult when using a single indicator to characterize pollutant emissions. Existing studies mostly consider multiple pollutant emissions and construct comprehensive indicators as measurements. In summary, this study draws on the research of Shao and Yang (2013) [48] and selects the annual industrial wastewater, industrial waste gas (SO2), and solid waste emissions per unit of output values in each province to construct a comprehensive index to measure environmental pollution. Meanwhile, the study adopts the entropy value method to synthesize and determine the weight of the environmental pollution variables by drawing on the studies of Jin et al. (2020) [49].

The calculation process is as follows:

$$std.x_{tij} = \frac{x_{tij} - \min\{x_j\}}{\max\{x_j\} - \min\{x_j\}} + 1 \tag{6}$$

where x_{tij} xtij denotes the jth indicator belonging to the i sample in the tth year.

Next, the normalization is performed to calculate the weight of std.xtij as follows:

$$P_{tij} = \frac{std.x_{tij}}{\sum_{t=1}^{T} \sum_{i=1}^{m} std.x_{tij}} \tag{7}$$

where T is the number of periods and m is the number of cross sections.

Afterward, its entropy value is calculated as follows:

$$E_j = -\frac{1}{\ln(T \times m)} \sum_{t=1}^{T} \sum_{i=1}^{m} P_{tij} \ln P_{tij} \tag{8}$$

The final calculation yields a composite index reflecting the level of pollutant emissions in each province as:

$$W_j = \frac{1 - E_i}{\sum_{j=1}^{n} (1 - E_i)} \tag{9}$$

$$EQ_{ti} = P_{tij} W_j \tag{10}$$

where n denotes the number of subindicators included in this composite index.

3.5.2. Explanatory variables

Environmental regulation is the explanatory variable. Turrent measures of environmental regulation can be divided into direct and indirect. The former directly characterizes the intensity of environmental regulation using input-based indicators, such as the amount of investment in environmental protection. Meanwhile, the latter indirectly uses concepts and variables that reflect the effect of environmental regulation policies, such as the sulfur dioxide removal rate and the composite index composed of the industrial smoke (dust) removal rate [50]. In essence, environmental regulation is a constraint on people's behavior; moreover, the effect of the policy is not merely a result of environmental regulations but also that of combined factors, including human influence. As such, indirect measurements are inevitably biased, and this study selects input-based indicators for measurement. The command-and-control regulation is borrowed from Ren Shenggang et al. (2018), who used the number of environmental administrative penalty decisions in each province in that year [51]. The market-incentive regulation is borrowed from Qu Xiao'e (2018), who used the total amount of sewage charges collected in each province [52]. Finally, the public participation regulation instrument is borrowed from Wu Jiannan et al. (2016), who used the total number of letters received from the public in each province's environmental protection system [53].

3.5.3. Mediating variables

Technological innovation is the mediating variable. Drawing on Xiao Liping and He Jingyuan (2015), product and process innovations are measured separately by using expenditures on new product development and expenditures on technological innovation [54]. Patent data are not used because the number of patents is overstated because of the greening behavior and symbolic innovation of enterprises under environmental regulations. By comparison, the use of expenditure measures can more accurately reflect the innovation investment of enterprises.

3.5.4. Control variables

To ensure the accuracy of the estimation results and prevent the omission of variables, we have selected the following as control variables on the basis of previous studies: level of economic development, which is measured by GDP per capita of each province; level of openness to the outside world, which is expressed by the proportion of total foreign direct investment utilized to GDP in each province in that year; and industrial structure, which is expressed by the ratio of tertiary industry to gross domestic product of secondary industry in each province. For the industrial structure, a larger value of the ratio indicates more reasonable industrial structure of the province in that year, which are regional dummy variables.[1]

3.5.5. Data sources and selection

This study uses panel data from 30 provinces, cities, and autonomous regions of China (excluding Tibet and Hong Kong, Macao, and Taiwan) for empirical analysis. The data are mainly obtained from the China Statistical Yearbook, China Environmental Statistical Yearbook, China Environmental Yearbook, and the China Science and Technology Statistical Yearbook. All monetary categories are adjusted with constant prices using 2011 as the base period to eliminate the effect of price changes. Notably, the environmental statistical scope and publication of wastewater, waste gas, and solid waste in several yearbooks changed after 2010. For example, the expansion of the statistical scope of China Environmental Statistics Yearbook led to inconsistencies in the statistical caliber before and after 2010. Therefore, the range of 2011–2020[2] is used as the sample data observation interval.

4. Analysis of empirical results

In view of the possible endogeneity between environmental regulations and pollution emissions due to mutual causality, the main explanatory variables, which are the lags of each environmental regulation method, are set as instrumental variables. The instrumental variable method is used for regression estimation, and the LM and F statistics values are reported. This approach demonstrates that the instrumental variables that have been selected for the study are reasonable and present no possible influence of endogeneity on the estimation results.

4.1. Stationary test and cointegration test

The study selected two methods for the unit root test, namely, the LLC test and the Fisher-PP test. This operation aims to examine the smoothness of the main variables and the robustness of the test. The original hypothesis is "H0: contains unit root." The results of the test showed that the test values of all variables rejected the original hypothesis at the 5% level, thus indicating that they are all stable series. Detailed results are presented in Table 1.

Further, to avoid the pseudoregression phenomenon, the Kao test in the EG two-step cointegration test is utilized to determine the cointegration. Here, the original hypothesis is "H0: No cointegration exists." The test results show that the regression of all the main explanatory variables with the explanatory variables rejects the original hypothesis at the 1% level. It shows that a long-run equilibrium relationship exists in the panel data used in this study. Detailed results are presented in Table 2.

4.2. Analysis of pollution abatement effects of environmental regulations

Columns 2 and 3 of Table 3 show that the command-and-control regulation and its squared coefficient are not significant, thereby

[1] Ideally, some province/region-specific variables should have been included as control variables in the pollution model. However, because the relevant data are not robust at present, the addition of relevant control variables is limited by the insufficient data. Moreover, the measurements of the variables in question are not widely recognized in academic research, and their robustness remains to be tested.

[2] The reason for the missing data before 2010 is that around 2009–2010, the statistical rules for the data in question changed and consistency became non-existent. Therefore, to ensure the validity of the study, the study had to ensure that the data for all the variables had the same connotation and measurement in each year, so the data before 2010 was discarded. The reason for not reflecting the data after 2020 is that there is a lag in the publication of the relevant data yearbooks from 2020 onwards, and the relevant data covered in this paper have not yet been fully disclosed as of today. To avoid the unbalanced phenomenon of the panel data and pursue the balanced panel data, the post-2020 data are not considered.

Table 1
Unit root test.

Variables	LLC	Fisher-PP	steady
ORDER	−3.21565 (0.0000) ***	35.32156 (0.0000) ***	stable
MRKT	−4.15462 (0.0001) ***	40.12564 (0.0000) ***	stable
PUBPA	−5.16524 (0.0000) ***	60.15486 (0.0000) ***	stable
EMC	−3.21654 (0.0000) ***	71.12562 (0.0105) **	stable
ISTR	−8.21546 (0.0001) ***	91.32564 (0.0000) ***	stable
OPEN	8.95412 (0.0000) ***	88.32514 (0.0004) ***	stable

***, **, and * indicate 1%, 5%, and 10% significance levels, respectively.

Table 2
Cointegration test.

dependent variable	explanatory variable	ADF	P	test results
Environmental pollution	ORDER、MRKT、PUBPA	−4.2315	0.000	reject
Product innovation	ORDER、MRKT、PUBPA	−3.7951	0.004	reject
Technological innovations	ORDER、MRKT、PUBPA	−2.1254	0.000	reject

indicating that it does not play a pollution reduction effect. Thus, Hypothesis 1 is not verified. Given the abovementioned change in the statistical caliber of the data, the current study period is 2011–2020, which is shorter and more backward than that of previous studies. Therefore, we suggest that the reason for the rejection of Hypothesis 1 is the period heterogeneity in the regulatory effect of command-and-control regulation tools. This inference is verified in the extended analysis. Second, Columns 4 and 5 show that the coefficients of market incentive regulation on pollution emissions are significantly negative at the 1% level, thus indicating that market incentive regulation can play a suppressive role on pollution emissions and cause a pollution abatement effect. Thus, Hypothesis 2 passes the test. Furthermore, the squared term of market-incentive regulation does not have a significant effect on pollution emissions, thus indicating that the nonlinearity of the pollution reduction effect of market-incentive regulation is not significant in 2011–2020. Finally, according to the last two columns, the coefficient of public-participation regulation on pollution emission is significantly negative at the 5% level, thus indicating a significant pollution emission reduction effect. Public participation in environmental regulation shows a reasonable and effective role in promoting pollution emission reduction, thereby supporting Hypothesis 3. In addition, a comparative analysis of the estimated results shows that, in terms of promoting emission reduction, the public-participation type of regulation is the most effective, followed by the market-incentive type, and then the command-and-control type. Thus, China's environmental regulation system has begun to change from a dominant command-and-control type into a market-incentive and public-participation type jointly. The advantages of public-participation type of regulation have come into play.

4.3. Analysis of the mediating effect of technological innovation

Tables 4 and 5 show the estimation results of the model with the inclusion of technological innovation variables. The role of technological innovation in the relationship between environmental regulation and environmental pollution can be tested by combining the contents of Table 3. Table 4 shows that command-and-control, market-incentive, and public-participation

Table 3
Test results of heterogeneous type of environmental regulation and environmental pollution.

Models Variables	(1)	(2)	(1)	(2)	(1)	(2)
ORDER	−0.021	1.135				
$ORDER^2$		−1.137				
MRKT			−0.156***	−0.130*		
$MRKT^2$				−0.031		
PUBPA					−0.599**	−15.929*
$PUBPA^2$						16.097
EMC	0.068**	0.224	0.166***	0.161***	0.376**	−0.064
ISTR	−0.034	0.267	−0.018	−0.026	−0.079	−0.544
OPEN	−0.025*	−0.130	−0.008	−0.008	−0.077	−0.034
LM	3.627**	2.539*	8.127***	6.604***	9.843*	3.917*
F	12.414	5.112	13.418	4.986	12.439	5.832

environmental regulations have significant incentive effects on product innovation, thus verifying Hypotheses 4a, 5a, and 6a. Thus, the foundation is laid for studying the path of pollution reduction by environmental regulations. Furthermore, the Porter hypothesis is supported. At the same time, market-incentive and public-participation environmental regulations have a significant role in promoting process innovation, thus verifying Hypotheses 5b and 6b and further supporting the Porter hypothesis. However, command-and-control environmental regulations do not have a significant role in process innovation, thus rejecting Hypothesis 6b. To achieve environmental compliance as soon as possible and minimize their impact, enterprises do not implement process innovation with almost no short-term benefits.

Furthermore, the regression of the econometric model with technological innovation and environmental pollution is conducted, and the estimated results are presented in Table 5. Columns 4 and 6 show that, the overall market incentive and public participation instruments still produce pollution abatement effects after adding product innovation. However, the coefficients and their significance are reduced to different degrees. Combining with the results in Table 3 shows that product innovation plays a partial mediating role between the above two regulatory instruments and environmental pollution, thus verifying Hypotheses 8 and 9. However, specifically, the positive relationship between product innovation and environmental pollution is not only detrimental to pollution reduction but also inhibits the proreduction effect of environmental regulation. Most enterprises implement product innovation to increase profits, which can cover the increase in costs because of environmental regulation. This process subsequently increases production and sales costs, thus leading to an increase rather than a decrease of pollutant emissions. This outcome is contrary to the policy objective of environmental regulation. By comparison, the estimation results of the model including process innovation in Columns 5 and 6 show that the market-incentive and public-participation environmental regulations help to promote pollution reduction through process innovation, which also has a suppressive effect on environmental pollution. Therefore, Hypotheses 11 and 12 are verified. Given the insignificant pollution reduction effect of command-based regulation tools in this model, the test of indirect effect through product and process innovations is rejected, and Hypotheses 7 and 10 are not verified. In addition, under the market-incentive and public-participation types, product innovation provides greater incentives but has a smaller role in promoting emission reduction than process innovation. This result indicates that the type of technological innovation that is currently the main type of environmental regulation is not the most conducive to environmental improvement. Moreover, environmental policy orientation shows a bias.

4.4. Period heterogeneity analysis

Given that environmental pollution, environmental policy, and economic development are in constant change and development, their relationship may show different characteristics over time, and the effect of environmental regulation on pollution reduction is likely to exhibit period heterogeneity. Moreover, the findings show no nonlinearity among command-and-control environmental regulation failure, market-incentive environmental regulation, and environmental pollution. This result diverges from previous studies, which is likely to be because of the period heterogeneity of the relationship among variables. Therefore, we further conduct an empirical analysis using the same cross-sectional panel data from 2005 to 2010 to investigate the differences in the pollution abatement effects of heterogeneous environmental regulations over time.

The results are shown in Table 6, where the command-and-control environmental regulation significantly contributes to the reduction of pollutant emissions from 2005 to 2010. Thus, the command-and-control environmental regulation is effective in the early period of environmental regulation, which is consistent with Hypothesis 1. Then, combining with the estimated results in Table 3, this type of regulation fails in 2011 and after, which can be attributed to the significant reduction of environmentally illegal enterprises. These empirical results confirm the period heterogeneity of the pollution reduction effect of environmental regulation. Meanwhile, market-incentive environmental regulations and their relationship with environmental pollution from 2005 to 2010 is an inverted U-shaped curve. As the intensity of market-incentive environmental regulations increases, environmental pollution emissions first increase and then decrease because of the "increased emissions" caused by the low price of various emissions and the higher profits that enterprises can obtain at the early stage of regulation. However, in 2011 and later, market-incentive environmental regulations tend to have reasonable prices and cross the inflection point, thus confirming the existence of period heterogeneity. The above analysis explains the differences between this study and the previous literature in terms of research findings. Furthermore, it provides a quantitative verification of the developmental evolution of environmental regulation in China from command-and-control dominance to the prominence of the market-incentive type and finally to the rise of the public-participation type of environmental regulation.

Table 4
Test results of heterogeneous type of environmental regulation on technological innovation.

Models Variables	PINN	TINN	PINN	TINN	PINN	TINN
	(3)	(4)	(3)	(4)	(3)	(4)
ORDER	0.046*	−0.128				
MRKT			0.129**	0.086**		
PUBPA					0.279***	0.096*
EMC	0.463***	−0.127***	0.512***	−0.222**	0.375***	−0.210**
ISTR	−0.156**	−0.347***	−0.183***	−0.302***	−0.139***	−0.332***
OPEN	−0.036	0.149***	−0.015	0.110**	−0.016	0.136**
F	−0.002	0.333	0.013	0.308	0.018	0.332

Table 5
Impact of environmental regulation, technological innovation on environmental quality.

Models Variables	(5)	(5)	(5)	(5)	(5)	(5)
ORDER	−0.010	−0.013				
MRKT			−0.129**	−0.140**		
PUBPA					−0.235**	−0.650*
PINN	0.066**		0.045*		0.390***	
TINN		−0.022		−0.016*		−0.067*
EMC	0.045	0.071	0.133**	0.158***	0.048	0.395
ISTR	−0.013	−0.029	−0.008	−0.017	0.047	−0.088
OPEN	−0.026	−0.025	−0.011	−0.009	−0.040**	−0.087
LM	3.952**	3.643*	7.959***	7.832***	3.123*	7.425*
F	14.343	12.54	13.022	13.483	13.327	11.858

Table 6
Period heterogeneity analysis.

Models Variables	Environmental Quality (2005–2010)					
	(1)	(2)	(1)	(2)	(1)	(2)
ORDER	−1.383**	−0.844**				
ORDER2		1.047				
MRKT			0.202	0.999***		
MRKT2				−0.873***		
PUBPA					−0.166	6.102
PUBPA2						−5.985
EMC	−0.079	−0.035	−0.152*	−0.083	−0.070	−0.063
ISTR	−0.120	−0.081	0.060	0.158*	0.008	0.368
OPEN	−0.159	−0.057	−0.085	−0.071	−0.085	−0.082
LM	3.631*	3.491*	7.786***	7.157**	7.830*	4.880*
F	9.548	4.921	9.457	7.109	9.118	7.720

4.5. Robustness test

To ensure the robustness of the above estimation results, we have also conducted robustness tests by replacing the econometric model with different estimation models. The results are presented in Table 7.The three types of regulatory instruments are put into the regression using the following econometric models:

$$EQ_{it} = \beta_0 + \beta_1 ORDER + \beta_2 MRKT + \beta_3 PUBPA + \beta_4 X_{it} + \varepsilon_{it} \tag{11}$$

$$PINN_{it} = \beta_0 + \beta_1 ORDER + \beta_2 MRKT + \beta_3 PUBPA + \beta_4 X_{it} + \varepsilon_{it} \tag{12}$$

$$TINN_{it} = \beta_0 + \beta_1 ORDER + \beta_2 MRKT + \beta_3 PUBPA + \beta_4 X_{it} + \varepsilon_{it} \tag{13}$$

$$EQ_{it} = \beta_0 + \beta_1 ORDER + \beta_2 MRKT + \beta_3 PUBPA + \beta_4 PINN + \beta_5 TINN + \beta_6 X_{it} + \varepsilon_{it} \tag{14}$$

The connotations of the letters and symbols contained herein remain consistent with the preceding text

The results of the robustness tests are presented in Table 5. Comparing the results with the previous tables show no significant

Table 7
Robustness tests.

Models Variables	(11)	(12)	(13)	(14)
ORDER	0.035	0.080**	0.025	0.019
MRKT	−0.123***	0.031**	0.021*	−0.131***
PUBPA	−0.030*	0.367***	0.201***	−0.094***
PINN				0.228***
TINN				−0.096**
OPEN	−0.001	−0.002	0.008**	−0.003
EMC	0.004***	0.012***	0.004**	0.002**
ISTR	−0.002	−0.001	−0.005	−0.002
F	0.231	−0.007	0.163	0.248
Model	FE	FE	FE	FE
N	210	210	210	210
R-squre	0.0976	0.5218	0.1213	0.0004

change in the direction and significance of the main explanatory variables. The magnitude of relationships also remains unchanged, thus indicating that the study results are robust.

5. Summary, shortcomings, and future prospects

On the basis of the background analysis and literature review in the introduction, the present study explores the mechanism path of environmental regulation policies to fill the existing research gap. Clarifying the specific path of environmental regulation policy tools can provide rational suggestions for the current policymaking, promote the improvement of the level of policy practice, and make efforts to solve the environmental pollution problem. Thus, this study introduces three types of regulatory tools and two types of technological innovation modes. It constructs environmental pollution measurement variables and the framework model of "government regulation, enterprise response, and policy outcome." Through the data analysis of the above model, we can empirically test the chain effects of environmental regulation policies on technological innovation and technological innovation on environmental pollution. Passing the empirical test implies that the mutual influence relationship between variables is real and can thus provide behavioral policy recommendations for policymakers and business managers.

The results show no significant relationship between command-and-control regulation and environmental pollution. Meanwhile, market-incentive and public-participation regulations have significantly negative effects on environmental pollution and contribute to emission reduction. In the early stage of regulation, command-and-control regulation is more effective and better than the other two types of regulatory tools. Market-incentive regulation has a nonlinear relationship, while public participation regulation is insignificant with environmental pollution. These outcomes differ from the findings in the study period. As for the role of technological innovation, the results show that market-based and public participation regulations have significantly positive effects on product and process innovations, thereby supporting the Porter hypothesis. At the same time, product and process innovations partially mediate the effects of market-based and public participation regulations on environmental pollution, respectively. Finally, the comparative analysis shows that, among the three types of regulatory instruments, public participation regulation is the most effective, followed by market incentive regulation, and then command-and-control regulation. In terms of the innovation incentive effect of environmental regulation, product innovation is more influenced by market-incentive and public-participation type regulation. However, compared with product innovation, process innovation has better pollution reduction effect, thus indicating its greater capability of converting the effect of environmental regulation into the real reduction of pollutant volume. However, the current environmental regulation policy has not tilted toward this goal.

We expect that readers gain a new understanding of the specific ways in which environmental regulation affects environmental pollution after reading this article. Moreover, the new understanding can be applied to realize the practical value of these insights. On the basis of the above findings, this study suggests that one direction for future policy adjustment lies in optimizing command-and-control environmental regulation policies, strengthening environmental monitoring and enforcement, and enhancing their regulatory effects. Local governments must set reasonable environmental technology and performance standards according to the objective situations of economic, technological, and market development. Subsequently, they can avoid the phenomenon in which command-and-control regulations have fewer targets and lower standards than the current real levels. In addition, the dynamic adjustment of the specific standards of command-and-control regulation must be maintained, and the period from policy design to implementation must be reduced to minimize the lag of policy requirements and standards on the level of scientific and technological development and market maturity. In doing so, we can improve the degree of conformity between environmental regulation policies and objective reality in various places and optimize the effect of regulation. Second, we must focus on the role of market-based incentives in the environmental regulation system and further optimize the price setting of regulatory instruments and the emission trading market to maintain a reasonable range. At present, environmental taxes, emission fees, and emissions trading are conducive to promoting pollution abatement. However, their impact has not weakened or even reversed. Therefore, factors that may affect the effectiveness of market-based incentives require analysis, monitoring, and estimations to achieve timely adjustments according to market responses. Third, the role of the public in promoting pollution reduction merits attention. The public's environmental demands are highly important to establish perfect channels for reflecting environmental demands and disclose detailed environmental information and data, guide the formation of a green consumption culture. These demands can also create opportunities to increase focus on environmental education and support private nonprofit environmental organizations to uphold reasonable and legal environmental rights and advocacies. Fourth, the implementation of green technology innovation subsidies and tax incentives application and distribution mechanism reform can enhance the effectiveness of environmental regulation to achieve a reasonable mix with and technological innovation. The previous situation in which innovation subsidies and tax incentives are granted only on the basis of the number of patents must change. Furthermore, the environmental friendliness of innovation results and their application values must also be considered to avoid symbolic innovation and political innovation by enterprises. Thus, we can eliminate the use of "green" and "environmental protection" banners to obtain benefits. Innovation subsidies require strict application and issuance to ensure the effective implementation of environmental regulation policies.

The conclusions of this research carries significant theoretical and practical value. In terms of theory, the study comprehensively examines and empirically tests the various types and impacts of environmental regulations. Particularly, it highlights the mediating role played by different forms of innovation. The theoretical framework used in this study is novel and represents expansion and innovation from previous research systems. In practical terms, many countries and regions are currently grappling with environmental pollution and resource scarcity. Hence, effective environmental regulations are crucial in addressing these challenges. The current research surpasses the mere theoretical understanding of environmental regulations and delves into practical applications by discussing whether specific policy tools and innovative models match. The resulting conclusions and policy recommendations are highly practical and operable, thus providing a noteworthy contribution to the pertinent research.

However, this research has some limitations. First, the research data sources are limited, thereby leading to conclusions that are applicable only to certain regions and lacking a universal scope. Second, the study solely focuses the role of innovation, a key intermediate variable, in the effectiveness of environmental regulation and pollution control. In reality, numerous other variables have not been considered, and their inclusion in future research can lead to nuanced conclusions.

Data availability statement

All data generated and analyzed during this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Zhilong You: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Guisheng Hou:** Supervision, Conceptualization. **Min Wang:** Writing – review & editing, Writing – original draft, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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