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Could the environmental regulation promote green innovation? Evidence from China

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Abstract

Could the environmental regulation promote green innovation? This is a very controversial issue. In view of the fact that the existing literature only studies the relationship between the two, lacks effective heterogeneity research, and pays less attention to the deeper analysis mechanism between the two. This study fills the gap. This paper selects the panel data of 285 prefecture level cities in China from 2000 to 2019 for empirical research. The results show that environmental regulation has a significant and continuous positive impact on green innovation.From the perspective of heterogeneity, we find that cities with higher level of green innovation are suitable to improve the intensity of environmental regulation; Cities with low level of green innovation can not formulate high-intensity environmental regulation policies. The intermediary mechanism shows that under the situation of stricter environmental regulations, producers will pay more attention to the promotion and accumulation of human capital, and provide strong intellectual support for green innovation activities. The adjustment mechanism shows that the cities with high degree of marketization and financial R&D investment are conducive to strengthening the promotion of environmental regulation on green innovation. On the contrary, it weakens the role of environmental regulation in promoting green innovation. In addition, this paper uses SYS-GMM model and selects appropriate instrumental variables to solve the endogeneity problem of the model. We find that after reducing the endogeneity of the model, improving the intensity of environmental regulation can still promote the level of green innovation. Using SDM decomposition model, we find that environmental regulation has spatial spillover effect on green innovation, and the formulation of environmental regulation strategy is conducive to the coordinated development of regional green innovation.

Key words: Environmental regulation; Green innovation; Porter hypothesis; Restriction theory;

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Innovation compensation; Compliance costs

1. Introduction

Since China's reform and opening up, relying on demographic dividend and institutional dividend, China has rapidly promoted the process of industrialization, laying the foundation for the development of "world factory". But the rapid economic growth is at the cost of environmental pollution. As a result, China has quickly become the world's largest energy consumer and greenhouse gas emitter. According to the 2018 global environmental performance index jointly compiled by Yale University and other authoritative institutions in the United States, China's air quality ranks fourth from the bottom among 180 countries and regions, only surpassing India, Bangladesh and Nepal.Among them, the concentrations of PM2.5 and PM10 are far behind the international average annual standard. Climate problems such as "black confusion" and "haze on ten sides" aggravate health inequality, but also bring significant economic losses and reduce social welfare. According to the 2020 "Lancet Countdown China Report", the number of high temperature heat wave related deaths in China has risen by four times since 1990. The economic losses caused by high temperature related deaths in 2019 reached 13.6 billion US dollars, which is equivalent to the economic income of more than 1.3 million people in the same year.Focusing on the protection of ecological environment and promoting the sustainable development of economy and society is the proper meaning.

In order to curb the continuous deterioration of the ecological environment, the government continues to increase the intensity of environmental regulation, and strive to transform the denotative growth into the connotative growth of economic development mode. Strict environmental regulation is conducive to improving the ecological environment, but supervision will cause distortion of local government incentives. Driven by the "Official Promotion" assessment mechanism with economic growth as the core, local governments reduce environmental standards in order to attract the inflow of capital and production factors. By reducing environmental standards, producers can save "compliance costs" , leading to "bottom-up competition" (Ahlers & Shen, 2018). Under the guidance of the concept of scientific development, local governments include environmental quality indicators in their performance appraisal. As an important link between government environmental regulation and sustainable development of green economy, green innovation has become an important consideration of high-quality economic development (Zhang & Zhu, 2019). Different from traditional innovation, green innovation is an important development strategy of producers, which is related to the improvement of their ability and competitive position (Przychodzen, 2020). Green innovation takes into account both economic and environmental effects, and achieves the expected environmental and economic benefits by increasing green human capital for R&D of green products and new technologies (Li & Zeng, 2020).

In fact, there are still many controversies about whether environmental regulation can promote green innovation, and there is a lack of clear conclusions in academic circles. There are two main issues in the debate: the "Restriction Theory" and the "Porter Hypothesis". The "Restriction Theory" represented by neoclassical school believes that strict environmental regulation will reduce the competitiveness of producers. Because environmental regulation has greatly increased the operating costs of producers, hindered the desire of producers to actively participate in green innovation research and development activities, and reduced the production of green innovation products. This view is also known as "Compliance Cost Theory". Supporters of the compliance cost theory look for theoretical and empirical evidence around the constraint theory (Pierce, 2021; Pan et al, 2021). However, Porter hypothesis creatively proposes that the design of appropriate environmental regulation standards can promote producer innovation. Strict but reasonable environmental regulatory policies, such as Pigovian taxes and pollution permits, can encourage producers to internalize external uneconomic behavior, encourage producers to actively participate in green innovation research and development activities, increase green product output, and generate "innovation compensation" effect to offset the impact of compliance costs (Porter and Vander, 1995). Later, many scholars conducted a series of explorations around Porter's hypothesis and believed that the greater the intensity of environmental regulation, the more conducive to driving the development of regional green innovation levels, and there is a positive linear correlation (Rubashkina, 2015; Santis, 2017; Tang et al, 2019; Deng et al, 2020). So, does environmental regulation have a significant positive or negative impact on green innovation? Few scholars have been involved in effective heterogeneity research. Does the implementation of environmental policies need to be tailored to local conditions? Many scholars only pay attention to the relationship between the two, and the discussion of the important internal mechanism has not attracted the attention of the academic circles. What is the impact mechanism of environmental regulation and green innovation? To clarify the above problems, we can clarify the significant effects and channels between the two, and provide policy enlightenment for China to implement environmental regulation to promote green innovation.

The existing literature lays a theoretical foundation and logical starting point for this study. Based on this, the marginal contribution of this paper is as follows: first, the research perspective. Due to the problem of data availability at the level of prefecture level cities in China, there are few literatures on this topic at the level of cities. City is the concentrated embodiment of modern economic and social civilization. By obtaining urban micro data, we can ensure that the research results are more reliable and reasonable, and open up a new research perspective. Second, research experience. In this paper, quantitative research is used to provide more abundant empirical information, and dynamic situation is used to investigate the long-term application effect of conclusions. Due to the heterogeneity of the implementation intensity of environmental regulation and the degree of green innovation in different cities, the implementation standards of environmental regulation policies may not meet the requirements of each city. Therefore, this paper strengthens the analysis and discussion of the heterogeneity. In addition, this paper uses SYS-GMM model to solve the endogeneity problem in the existing literature, and reduces the estimation error caused by endogeneity by selecting appropriate instrumental variables. We choose the spatial Dubin model to investigate the spatial effects of environmental regulation and green innovation. Third, research mechanism. What are the specific channels to influence environmental regulation and promote green innovation? There is a lack of discussion on the internal mechanism of this topic in the existing literature. This paper will further introduce the mediating and moderating mechanisms to examine the influence channels of research topics. This study helps to clarify the direction of environmental regulation on green innovation. Through strengthening the analysis of heterogeneity and endogeneity, and clarifying the internal mechanism, it can guide the application of environmental regulation policy tools in green innovation in China.

The rest of this paper is arranged as follows: the second part puts forward the theoretical hypothesis of environmental regulation and green innovation. The third part describes the use of empirical analysis methods, including standard empirical model, estimation method, index measurement and data sources. The fourth part introduces the estimation results and empirically analyzes the relationship between environmental regulation and green innovation, including heterogeneity analysis and endogenous test. The fifth part discusses the internal mechanism of their relationship, including the mediating effect and regulatory effect. The sixth part is the summary of this study, and puts forward a series of policy recommendations.

2. Literature review and theoretical hypothesis

The impact of environmental regulation on green innovation is mainly based on the comprehensive effect of "Compliance Cost Effect" and "Innovation Compensation Effect". Environmental regulation will produce greater innovation compensation effect to offset the adverse factors brought by the cost of compliance. It mainly comes from the following three reasons: (1) Cost saving. For producers, the cost of not complying with environmental regulations is high. In order to avoid the increase of production cost caused by higher environmental regulation, producers tend to make appropriate changes to reduce the compliance cost. Producers should carry out green process improvement and technology research and development to reduce production costs and improve production efficiency (Meng et al, 2020). (2) Promote competition. Producers are faced with three kinds of external environmental pressures: the pressure of environmental regulations, the pressure of customers and suppliers' stakeholders, and the pressure of imitation competition to maintain their market share (Cai & Li, 2018). Environmental regulation promotes producers to accept new ideas, stimulate their creative thinking, improve product quality and environmental performance, and gain market competitive advantage (Li et al, 2019). (3) Social responsibility. Producers do not always pursue profit maximization, and meeting social needs and goals is also an important factor for them to consider. In order to maintain the legitimate needs of consumers and the government, producers are more willing to carry out transformation, which can help producers gain a sense of social responsibility and achieve additional profits by establishing a green image (Du et al, 2020).

H1: Environmental regulation can improve the level of green innovation.

In the face of more stringent environmental regulations, producers' pursuit of compliance depends on their ability to understand, absorb and commercialize external knowledge (Leblebici et al, 1991). Therefore, having a high level of green innovation will increase organizational flexibility and make it possible to adapt to the higher pressure of environmental regulation. On the one hand, with the improvement of individual or regional green innovation level, the public awareness of environmental protection is constantly enhanced, and the government supervision is correspondingly increased. Regions with higher level of green innovation have higher level of green absorptive capacity and will have the opportunity to get more preferential tax treatment from the government. High intensity of environmental regulation will encourage regions to increase green innovation investment, and promote producers, especially those with high pollution and high emission, to obtain competitive advantage in green transformation (Delmas, 2011; Liao & Shi, 2018). On the other hand, regions with low green absorptive capacity can not bear the pressure of environmental regulation. Although the public's awareness of environmental protection has been strengthened and the government's supervision has increased, it is difficult to meet the compliance requirements because of the lack of affordability, which leads to the producers' unwillingness to increase green innovation investment (Shen et al, 2019). To sum up, higher level green innovation regions can better identify, evaluate and utilize new market opportunities, and transform high-intensity environmental regulation pressure into the driving force to improve their green innovation level (Zhang et al, 2019).

H2: Strong green innovation area is suitable for improving the intensity of environmental regulation, while weak green innovation area is not suitable for making high-intensity regulation.

Under the pressure of environmental laws and policies, producers must take active measures to deal with environmental challenges (Chan, 2005). When producers implement green innovation strategy, managers integrate producer resources through green performance management and compensation practice, cultivate internal staff and introduce innovative talents, so that they can make greater efforts to produce new ideas, methods and actions, and effectively enhance human capital (Ma et al, 2019). According to Romer's human capital theory, human capital is of great significance to productivity growth (Romer, 1990). Human capital is the basic element of knowledge economy and the core strategic resource of sustainable competitive advantage (Song & Yu, 2018). Regions with high human capital have stronger technology attraction and diffusion ability, which is conducive to the promotion and application of new technologies, and tend to accept the concept of environmental protection and comply with environmental regulations, which is conducive to reducing environmental pollution (Bano, 2018). Human capital should increase the use of green technology, effectively avoid the "Resource Curse" and transform it into "Resource Gospel" by giving full play to skilled equipment operation and technology application ability, so as to realize the knowledge driven sustainable economic development mode (Singh, 2020). Human capital through green training and education can help producers improve the level of green supply chain management, sustainable human resource management and practice, reduce costs and gain good social reputation (Albort-Morant et al, 2018).

H3: Environmental regulation can further improve the level of green innovation by promoting the improvement of human capital.

More and more attention has been paid to market-oriented green innovation in China. The market mechanism can stimulate the enthusiasm of producers, and the market price can reasonably reflect the scarcity of resources and the supply and demand of products, both of which provide reasonable guidance for production allocation (Filipovic, 2019). Effective market is conducive to cross regional competition and cooperation. Cities with a higher degree of marketization have less redundant construction, and form economies of scale through mergers, acquisitions and opening up new markets to provide green innovation efficiency (Chen et al, 2021). Producers can improve their business performance through green innovation. Producers in the same industry "Strive For Survival By Innovation", forcing producers to leave the comfort zone and provide new capabilities and products, resulting in "Escape From Competition Effect" (Albort et al, 2018). Market based tools, such as sewage charges, environmental subsidies, emissions trading and other market means, internalize the externality of pollution, reduce the marginal cost of pollution control, and obtain more compensation for emission reduction (Liao, 2018). In addition, under the imperfect market mechanism, due to unclear property rights, regions with more abundant natural resources are more likely to face rent-seeking, corruption and opportunism, which will hinder the development of green innovation and R&D activities (Pan et al, 2019).

H4: The regions with high degree of market development can strengthen the promotion of environmental regulation on green innovation.

Green innovation has the characteristics of "Double Externalities" of knowledge spillover and positive environmental externalities. Producers need to pay but can not get all the returns, and lack the motivation to provide R&D funds. Green innovation is an active investment mode with long investment cycle and large resource investment. Because of the market demand, the change of key technical personnel, the shortage of capital supply and other reasons, the producers bear a greater risk of green innovation. Imperfect market pricing system is prone to "Free Riding" behavior. The regulatory role of the market alone is not enough to promote the level of green innovation to achieve social optimum (Wang et al, 2018; Li, 2019). Financial R&D investment plays a vital role in green innovation activities. Endogenous growth theory shows that the intensity of financial R&D investment has a positive impact on the production sector, and efficient public R&D system can make better use of private R&D funds (Conte, 2013). Financial R&D investment can send a "Signal" to the market, guide producers and society to participate in green R&D, cultivate green innovative talents, alleviate the problem of lack of funds for relevant producers, and reduce the cost and risk of green R&D (Yi, 2020).

H5: Regions with more financial R&D investment can strengthen the role of environmental regulation in promoting green innovation.

3. Research design

3.1.Source of sample data

In view of the lack of data in some cities such as Turpan and Linzhi, the sample is removed, and a total of 5700 samples of 285 cities in China from 2000 to 2019 are selected.Among them, the number of urban green patents comes from the retrieval of the State Intellectual Property Office and the matching of the classification standards of the world intellectual property organization.

The data of environmental regulation comes from the work report of the city government, and is mined by Python technology. The instrumental variable air circulation coefficient is based on era interim meteorological data published by European Center for weather forecasting (ECMWF), and is extracted by overlaying grid data with urban base map through ArcGIS. The other indicators are from the statistical yearbook of Chinese cities and the statistical yearbook of local cities.In order to reduce the heteroscedasticity of data, we use logarithm to deal with the data. We use 1% winsorize to deal with the main continuous variables.

3.2.Model construction

Considering the impact of environmental regulation on green innovation, this paper takes the level of green innovation as the explained variable and environmental regulation as the explanatory variable. In addition, there may be inertia in the level of green innovation, that is, the previous intensive level has an impact on the current intensive level. A dynamic model is constructed as follows.

$$\ln GI_{it} = \alpha_0 \ln GI_{it\text{-}1} + \alpha_1 \ln ER_{it} + \alpha_i \ln X_{it} + u_i + v_t + \varepsilon_{it} \quad (1)$$

Among them, $\ln GI_{it}$ is the green innovation level of i city in t year; $\ln ER_{it}$ is the environmental regulation intensity of i city in t year; $\ln X_{it}$ is the control variable, α is the regression coefficient, μ_i and v_t are individual and time fixed effects, and ε_{it} is the residual term.

3.3.Index selection

(1) The explained variable is green innovation (*lnGI*). Green technology refers to following the law of ecological economy, adopting "Pollution-Free" and "Less Pollution-Free" technologies to save resources and energy and reduce ecological environmental pollution. In 2010, the World Intellectual Property Organization (WIPO) launched the "International Patent Classification Green List[2]" to facilitate retrieval of environmentally friendly technologies. According to the United Nations Framework Convention on climate change, green patents are classified into seven categories: energy conservation, alternative energy production, transportation, waste management, administrative supervision and design, nuclear power, agriculture and forestry. According to the above division basis and the IPC information of the patent classification number of the State Intellectual Property Office, the matching identification and accounting can be divided into the core measurement indicators of green innovation activities in various cities.

(2) Core explanatory variable: Environmental regulation (*lnREG*). In order to further discuss the impact of government environmental governance on green innovation, we need to construct

[2] http：//www.wipo.int /classifications /ipc/en/ est.

appropriate environmental regulation variables to achieve the purpose of this paper. At present, the academia mainly measures the government's environmental regulation by means of pollution control investment cost, pollutant emission intensity, pollution tax rate and the number of environmental protection personnel. But these methods often produce many problems, such as only reflecting one aspect of the government governance environment. That is difficult to measure the overall picture of government governance policy. Therefore, similar to Chen et al. (2018), the frequency of environment related words in the government work reports of cities is selected as the proxy variable of environmental regulation. In this paper, python software is used to manually sort out the words related to the environment in the government work report. The frequency of search words are: ecology, environmental protection, environmental protection, emission reduction, pollution, air, green, carbon dioxide, pollution, energy consumption, low carbon, chemical oxygen demand, sulfur dioxide, PM2.5, PM10 and so on. The reasons for the better applicability of the index are: First, it can well reflect the overall picture of the government's environmental governance policies. Second, it can avoid reverse causality and meet the exogenous requirements of environmental regulation. Third, It can alleviate the unscientific and unreasonable measurement of environmental regulation caused by the lack of more data at the urban level.

Fig.1 shows the time series characteristics of the measurement results of environmental regulation and green innovation indicators from 2000 to 2019. The number of environmental words increased from 287 in 2000 to 10464 in 2019, with an average annual growth rate of 25.12%. The number of green innovation patents increased from 8058 in 2000 to 454224 in 2019, with an average annual growth rate of 24.21%. Environmental regulation and green innovation have a similar growth trend and a positive correlation. This means that the concept of sustainable development is deeply rooted in the hearts of the people, the government continues to improve the environmental laws and policies system, and green innovative technology has made a breakthrough.

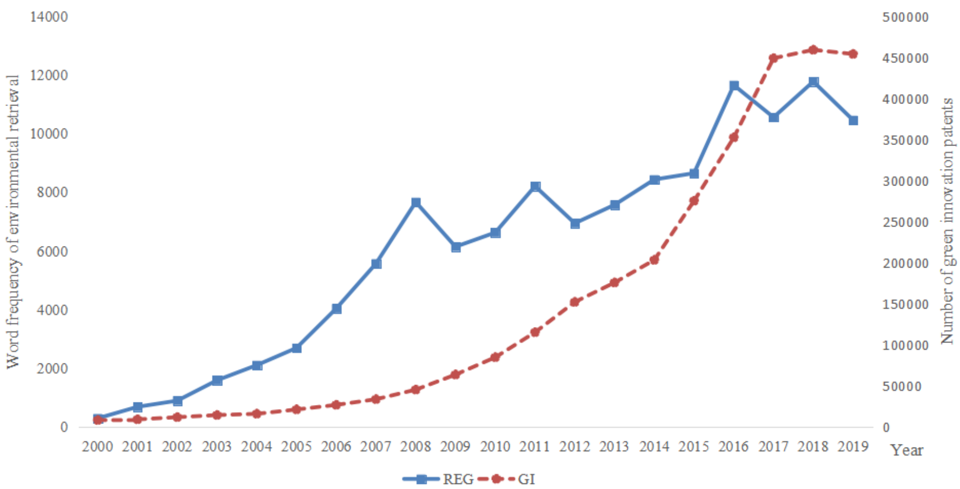

Fig.1 Time sequence characteristics of *ER* and *GI*

Fig.2 shows the spatial distribution of environmental regulation and green innovation (Taking 2019 as an example). We find that environmental regulation presents the spatial distribution characteristics of "Differentiation". This may be due to the wide coverage of China's land, unbalanced carrying conditions of regional resources and environment, regional development stage, industrial structure and environmental governance needs and other reasons, forming a "Classified Guidance" policy system.

The spatial distribution of green innovation has two main characteristics: First, the "Cluster Effect" is significant, forming the spatial pattern of "Four Cores, Three Clusters, Two Belts and Many Points". With Beijing, Shanghai, Guangzhou and Shenzhen as the "Four cores", it radiates the "Urban Agglomerations" of Beijing Tianjin Hebei, Yangtze River Delta and Pearl River Delta. The eastern coastal economic belt and Yangtze River economic belt form a "Two Belt" distribution, and Wuhan, Xi'an, Chongqing and other cities form a multi-point "Growth Pole". Cities rely on their economic development, resource endowment, human capital, innovation factors and location policies to promote the development of urban green innovation level. Second, "Matthew Effect" is highlighted. The green innovation level of East China and South China is absolutely superior. In addition, regional industries complement each other and have strong comprehensive competitiveness, which further attract green innovation elements to accelerate agglomeration. Therefore, the difference of green innovation development will be further expanded.

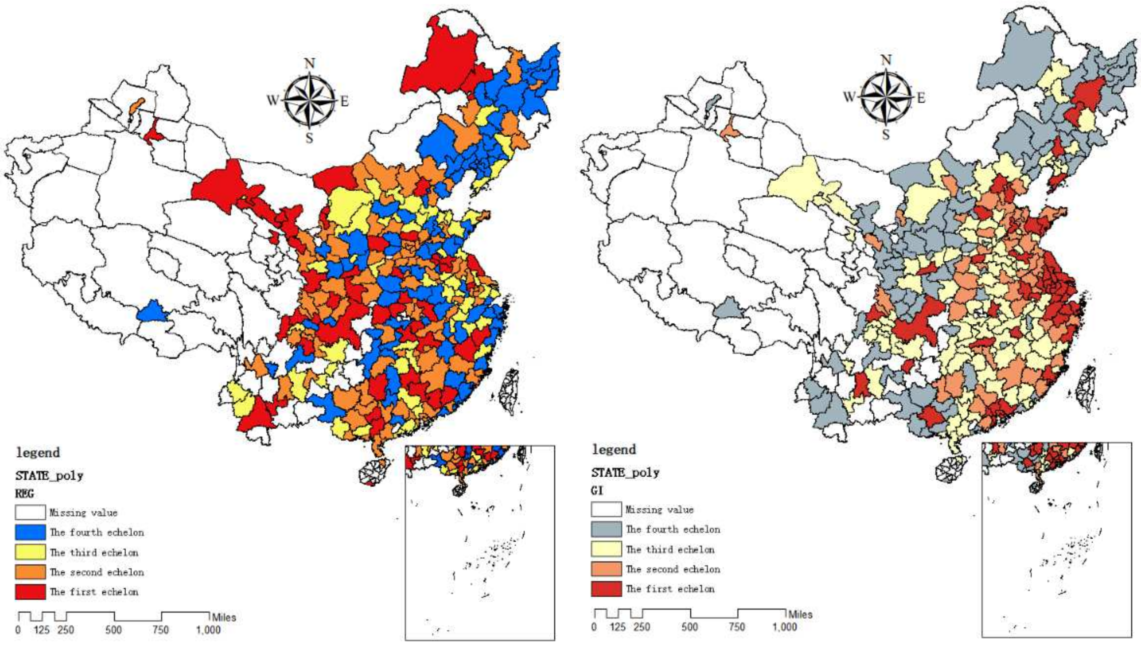

Fig.2 Spatial distribution characteristics of *ER* and *GI*

(3) Mediators and moderators. This paper focuses on the mediating mechanism of environmental regulation on green innovation from the perspective of human capital. Human capital (*lnEdu*) is measured by the number of students per ten thousand. In addition, This paper examines the regulatory effect mechanism of environmental regulation on green innovation from the perspective of marketization level and Government R&D expenditure. This paper uses the proportion of private and individual employment in the total employment to measure the level of marketization (*LnMar*). Government R&D expenditure (*LnPte*) is measured by per capita financial science and technology expenditure.

(4) Instrumental variables. To identify the causal relationship between environmental regulation and green innovation, the biggest challenge is to solve the endogenous problem of environmental regulation. We use SYS-GMM to reduce the endogeneity of the model. The instrumental variables are the explained variable with a lag of one period (*L.lnGI*), the mean value of environmental regulation (*lnPREG*) and the coefficient of air circulation (*lnVC*). The selection basis of instrumental variables is shown in the endogeneity analysis section below.

(5) Control variables. ① Population density level (*lnCity*): it is measured by dividing the population by the administrative area. ②Infrastructure construction (*lnInstra*) is measured by highway mileage. ③Level of opening to the outside world (*lnFdi*): FDI is the amount of foreign capital actually used in the current year. According to the annual average exchange rate of RMB against the US dollar published in the annual report of the State Administration of foreign exchange, the actually utilized foreign capital is converted into the price of RMB, and then the proportion of FDI in GDP is calculated to measure the level of opening to the outside world.④The level of financial development (*lnFin*) is expressed by the proportion of loan balance of financial institutions in GDP.

Table 1: Statistical Analysis of main variables

Variable	Indicator meaning	Obs.	Mean	Std.Dev.	Min	Max
lnGI	Green Innovation	5700	3.5715	1.9688	0.0000	9.9617
lnREG	Environmental regulation	5700	2.5761	1.3108	0.0000	4.7095
lnCity	Population density level	5700	5.7118	0.9252	1.5476	9.3557
lnInstra	Infrastructure construction	5700	8.9363	0.7888	6.6593	10.2954
lnFdi	Level of openness	5700	0.9199	0.6367	0.0178	2.6326
lnFin	Financial development level	5700	4.4401	0.5430	3.3565	6.0133
lnEdu	human capital	5700	4.2390	1.2814	1.8074	7.4612
lnMar	Marketization level	5700	4.2957	0.7195	0.9719	7.4466
lnPte	Financial R&D investment	5700	3.8492	1.2621	1.3906	7.4088
lnVC	Air circulation coefficient	5700	7.3525	0.3000	6.5472	8.2415

Note: Data values are transformed into logaritmic form.

4. Econometric methodology

4.1.Benchmark regression

The baseline regression results are reported in Table 2. (1) - (3) listed as static panel model.（4) - (6) list the dynamic panel model as the explained variable of lag phase I to test whether the model has long-term robustness. The fixed effects of city, time, city and time are introduced into the model. Select the model with good goodness of fit as the analysis benchmark, and the regression results show that: In the short term, environmental regulation can significantly promote green innovation (β= 0.0170, P < 0.010, Model 3). In the long run, the early green innovation has a dynamic impact effect, which promotes the current green innovation and has a significant and continuous positive impact (β= 0.0160, P < 0.010, Model 6). It shows that strict environmental regulation is conducive to promoting the development of green innovation technology (Peng et al, 2021), and verifies hypothesis H1.

Table 2: Benchmark regression

Variable	*lnGI*					
	(1)	(2)	(3)	(4)	(5)	(6)
L.lnGI				0.735***	0.888***	0.499***
				(0.00850)	(0.00619)	(0.0117)
lnREG	0.285***	0.0212**	0.0170*	0.0907***	0.0351***	0.0160*
	(0.0120)	(0.0104)	(0.0102)	(0.00828)	(0.00866)	(0.00882)
lnCity	2.190***	0.861***	0.688***	0.600***	0.102***	0.363***
	(0.127)	(0.0474)	(0.0911)	(0.0865)	(0.00889)	(0.0808)
lnInstra	1.550***	0.244***	0.200***	0.449***	0.0588***	0.0942***
	(0.0324)	(0.0323)	(0.0350)	(0.0254)	(0.0103)	(0.0321)
lnFdi	-0.332***	-0.0516***	-0.0806***	-0.0711***	0.0692***	-0.0457***
	(0.0251)	(0.0182)	(0.0182)	(0.0170)	(0.0119)	(0.0161)
lnFin	1.103***	0.309***	0.235***	0.266***	0.131***	0.137***
	(0.0273)	(0.0316)	(0.0321)	(0.0205)	(0.0161)	(0.0280)
Constant	YES	YES	YES	YES	YES	YES
Urban fixed	YES	NO	YES	YES	NO	YES
Year fixed	NO	YES	YES	NO	YES	YES
Observations	5,415	5,415	5,415	5,415	5,415	5,415
Number of id	285	285	285	285	285	285
R-squared	0.7200	0.8653	0.8660	0.8818	0.8806	0.9004

Note: In parentheses denote the standard error of the respective coefficients, ***/**/* indicates the significance at the 1%/5%/10% levels, respectively.

4.2.Endogeneity test

Because the level of R&D tendency and expenditure of producers will also affect the environmental regulation faced by producers, there is a two-way causal relationship. In order to solve the endogenous problem, this paper refers to Fisman & Svensson (2007) and Hering & Poncet (2014), and takes the average level of environmental regulation (*lnPREG*) and air circulation coefficient[3] (*lnVC*) as the instrumental variables of environmental regulation. Taking the average value of environmental regulation in different cities as an instrumental variable is not directly affected by the behavior of a single producer, but the average level of a city is directly related to the explanatory variable, so it can be used as an instrumental variable of environmental regulation. According to the ArcGIS software, the grid data is superimposed on the map of Chinese cities, and the air circulation coefficient of the corresponding city and year is matched.The air circulation coefficient only depends on natural phenomena such as regional climate conditions. In addition to affecting the degree of environmental regulation, there is no other mechanism between air circulation coefficient and green innovation, which meets the requirements of "Correlation" and "Exogenous" hypothesis, so it can be used as a instrumental variables of environmental regulation.

Table 3 reports the regression results of system instrumental variables (SYS-GMM). The first column is the lag period, and the explained variables are used as instrumental variables. The second column is the average of environmental regulation with instrumental variables. The third column is adding instrumental variable air flow coefficient to further reduce the endogenous problem of the model. It can be found that the sequence correlation test rejects the original hypothesis that there is no first-order autocorrelation for each estimated residual sequence, but does not reject the original hypothesis of second-order autocorrelation. Combined with Sargen test and Hansen test, it can be seen that the construction of instrumental variables in SYS-GMM is reasonable. The results show that environmental regulation has a significant positive impact on green innovation (β= 985, $P < 0.005$, Model 1; β= 891, $P < 0.001$, Model 2; β= 624, $P < 0.005$, Model 3). It shows that after reducing the endogeneity of the model, improving the intensity of environmental regulation can still promote the level of green innovation, and the empirical results are relatively stable.

Table 3 : Estimation of instrumental variables

Variable	*lnGI*		
	(1)	(2)	(3)
L.lnGI	0.529***	0.573***	0.476**
	(0.146)	(0.107)	(0.219)

[3] The air flow coefficient is equal to the wind speed times the height of the boundary layer. The era interim database of the European Center for medium range weather forecasts (ECMWF) provides the global 0. 75 degree × The wind speed (SI10) and boundary layer height (BLH) data at 10 meters height on 0.75 ° grid (about 83 square kilometers).

lnREG	0.985** (0.414)	0.891*** (0.282)	0.624** (0.295)
lnCity	0.405*** (0.122)	0.364*** (0.088)	0.446** (0.178)
lnInstra	0.0714 (0.0674)	0.064 (0.063)	0.189*** (0.0690)
lnFdi	0.129** (0.0556)	0.119*** (0.044)	0.110* (0.0602)
lnFin	0.308*** (0.0878)	0.281*** (0.073)	0.465** (0.186)
Constant	YES	YES	YES
AR(1)	-7.45*** (0.000)	-9.54*** (0.000)	-9.63*** (0.000)
AR(2)	1.18 (0.238)	1.56 (0.120)	1.49 (0.137)
Sargen test	0.308	0.749	0.388
Hansen test	0.360	0.869	0.407
Observations	4,275	4,275	4,845
Number of id	285	285	285

Note: In parentheses denote the standard error of the respective coefficients, ***/**/* indicates the significance at the 1%/5%/10% levels, respectively.

4.3.Spatial effect test

According to the first law of geography, there is correlation between things, and the correlation between things closer is higher than that between things farther (Tobler, 1970). In order to enhance the robustness of the model and whether there is spatial spillover, we use spatial model to measure spatial dependence. The spatial Durbin model considers the correlation of independent variables and the correlation between independent variables and dependent variables in adjacent areas. It is a composite model of spatial autocorrelation model and spatial error model. Therefore, the spatial Dobbin model is selected to analyze the spatial relationship between environmental regulation and green innovation. Without considering the spatial correlation, Hausman test rejected the original hypothesis at 1% significance level, so the fixed effect model was chosen. Considering the heterogeneity of the city, we choose the double fixed effect model of time and space. Finally, the dynamic model is considered by lagging the explained variable for one period. According to LeSage & Pace (2009), the regression coefficient of spatial Durbin model can not accurately explain the influence of explained variables and spatial spillover, so the decomposition model of dynamic spatial Durbin model is taken as the analysis focus.

Before spatial model analysis, we need to use Moran index to test the correlation of core indicators. The results show that the overall Moran index of green innovation and environmental regulation have passed the 1% confidence level test (Schedule 1), indicating that the overall spatial correlation degree of the two is high. The local Moran index is positively correlated (Fig. 1 and Fig.2), which indicates that there is a local spatial correlation between them, and the spatial model can be used for further analysis. Table 4 reports the regression results of the dynamic spatial Durbin decomposition model, in which (1) is the direct effect model, (2) is the indirect effect model, and (3) is the total effect model. The results show that environmental regulation has a positive correlation with local green innovation level (β= 0440, $P < 0.005$, Model 1), and has a significant role in promoting the level of green innovation in adjacent areas (β= 1670, $P < 0.005$, Model 2). It shows that environmental regulation has spatial spillover effect. With the gradual progress of ecological civilization construction, the central and local governments have frequent strategic interaction in environmental protection. The formulation of environmental regulation strategy has gradually changed into "Top-To-Top Competition", which is conducive to the coordinated development of regional green innovation (Peng, 2020).

Table 4: Spatial effect test

Variable	*lnGI*		
	(1)	(2)	(3)
lnREG	0.0440**	0.1670**	0.2110**
	（0.0178）	（0.0772）	（0.0886）
lnCity	0.4147**	1.8203***	2.2350***
	（0.1658）	（0.6780）	（0.7793）
lnInstra	0.1656***	-0.0359	0.1298
	（0.0632）	（0.2446）	（0.2717）
lnFdi	-0.0492	-0.0645	-0.1137
	（0.0337）	（0.1106）	（0.1198）
lnFin	0.2832***	0.1802	0.4634*
	（0.0602）	（0.2398）	（0.2685）
Urban fixed	YES	YES	YES
Year fixed	YES	YES	YES
Rho		0.1581***（8.74）	
Hasen Test		342.56***（0.00）	
AIC		12506.63	
BIC		12546.51	
N		5700	
R-squared		0.8973	

Note: In parentheses denote the standard error of the respective coefficients, ***/**/* indicates the significance at the 1%/5%/10% levels, respectively.

4.4.Heterogeneity analysis

Each city has the characteristics of unbalanced development, so it is necessary to investigate the policy differences of environmental regulation on local green innovation development in different cities.In order to verify whether this difference exists, this paper takes the sample median of environmental regulation and green innovation as the boundary, and divides the research objects into strong regulation (*RQ*) and weak regulation cities (*RR*), strong green innovation (*GQ*) and weak green innovation cities (*GR*), strong regulation and strong green innovation cities *RQ&GQ*), weak regulation and weak green innovation cities (*RQ&GQ*). For the division of areas, refer to Fig. 3 and Fig. 4.

Table 5 reports the heterogeneity analysis of the above different environmental regulations and green innovation characteristics. The results show that the zoning of environmental regulation can not reflect the direction of policy implementation (β= - 00319, P > 0. 010, Model 1; β= 00319, P > 0.010, Model 2). That is to say, strengthening or reducing the intensity of environmental regulation does not necessarily significantly promote the development of green innovation. The strong and weak zoning of green innovation is of guiding significance for policy implementation. In strong green innovation cities, we should increase the intensity of environmental regulation to promote the development of local green innovation (β= 0367, P < 0.001, Model 3). However, in weak green innovation cities, increasing the intensity of environmental regulation will significantly hinder the development of local green innovation (β=- 0367, P < 0.001, Model 4). The overlapping zoning of regulation strength and green innovation strength also has the guiding significance of policy implementation.In cities with the same characteristics of strong regulation and strong green innovation (Such as Beijing, Tianjin, Shenzhen, etc.), strengthening regulation can promote the development of green innovation (β= 0318, P < 0.001, Model 5). In cities with the same characteristics of weak regulation and weak green innovation (Such as Zhangjiajie, Chaoyang, Lhasa, etc.), there is no clear policy guidance (β= - 0146, P > 0. 010, Model 6). In a word, the strong green innovation city is suitable to improve the intensity of environmental regulation, and the innovation compensation effect of Porter hypothesis is significant. Weak green innovation cities can not formulate policies with higher regulation intensity, and the crowding out effect of compliance cost is obvious, which verifies the hypothesis H2.

Table 5 : Heterogeneity test

Variable	*lnGI*					
	(1)	(2)	(3)	(4)	(5)	(6)
L.lnGI	0.735***	0.735***	0.731***	0.731***	0.733***	0.734***
	(0.0115)	(0.0115)	(0.0114)	(0.0114)	(0.0116)	(0.0114)
lnREG	0.0924***	0.0892***	0.0774***	0.114***	0.0849***	0.0948***
	(0.0128)	(0.0107)	(0.0110)	(0.0128)	(0.0105)	(0.0105)
lnCity	0.600***	0.600***	0.595***	0.595***	0.602***	0.596***

	(0.202)	(0.202)	(0.202)	(0.202)	(0.203)	(0.202)
lnInstra	0.449***	0.449***	0.449***	0.449***	0.451***	0.449***
	(0.0312)	(0.0312)	(0.0311)	(0.0311)	(0.0312)	(0.0312)
lnFdi	-0.0713***	-0.0713***	-0.0699***	-0.0699***	-0.0698***	-0.0703***
	(0.0160)	(0.0160)	(0.0157)	(0.0157)	(0.0157)	(0.0160)
lnFin	0.266***	0.266***	0.267***	0.267***	0.267***	0.265***
	(0.0200)	(0.0200)	(0.0200)	(0.0200)	(0.0200)	(0.0202)
lnREG×RQ	-0.00319					
	(0.0127)					
lnREG×RR		0.00319				
		(0.0127)				
lnREG×G*Q*			0.0367***			
			(0.0125)			
lnREG×GR				-0.0367***		
				(0.0125)		
lnREG×RQ&GQ					0.0318**	
					(0.0135)	
lnREG×RR&GR						-0.0146
						(0.0151)
Constant	YES	YES	YES	YES	YES	YES
Urban fixed	YES	YES	YES	YES	YES	YES
Year fixed	YES	YES	YES	YES	YES	YES
Observations	5,415	5,415	5,415	5,415	5,415	5,415
Number of id	285	285	285	285	285	285
R-squared	0.8818	0.8818	0.8820	0.8820	0.8819	0.8818

Note: In parentheses denote the standard error of the respective coefficients, ***/**/* indicates the significance at the 1%/5%/10% levels, respectively.

5. Further analysis

5.1.Mediation and regulatory effect model

In order to further explore the relationship between environmental regulation and green innovation, we still need to study its internal mechanism. This paper draws on the intermediary and regulatory effect mechanism model constructed by Chan (2021) to identify the mechanism of environmental regulation on green innovation. On the basis of (1), model (2) (3) is added to the test process of mediating effect, and the test process of moderating effect is (4) - (5).

$$\ln Edu_{it} = \alpha_0 \ln Edu_{it\text{-}1} + \alpha_1 \ln ER_{it} + \alpha_i \ln X_{it} + u_i + v_t + \varepsilon_{it} \quad (2)$$

$$\ln GI_{it} = \alpha_0 \ln GI_{it\text{-}1} + \alpha_1 \ln ER_{it} + \alpha_2 \ln Edu_{it} + \alpha_i \ln X_{it} + u_i + v_t + \varepsilon_{it} \quad (3)$$

$$\ln GI_{it} = \alpha_0 \ln GI_{it\text{-}1} + \alpha_1 \ln ER_{it} + \alpha_2 \ln Edu_{it} + \alpha_3 \ln Adj_{it} + \alpha_i \ln X_{it} + u_i + v_t + \varepsilon_{it} \quad (4)$$

$$\ln GI_{it} = \alpha_0 \ln GI_{it\text{-}1} + \alpha_1 \ln ER_{it} + \alpha_2 \ln Edu_{it} + \alpha_3 \ln Adj_{it} + \alpha_4 \ln ER_{it} \cdot \ln Adj_{it} + \alpha_i \ln X_{it} + u_i + v_t + \varepsilon_{it} \quad (5)$$

In the above formula, $LnEdu_{it}$ is the intermediary variable, which represents the human capital of region i in year t, $LnAdj_{it}$ is the regulatory variable, which represents the marketization level ($LnMar_{it}$) and government research investment ($LnPte_{it}$) of region i in year t. The setting of other variables is the same as that in formula (1).

5.2.Mediating effect test

In order to increase the persuasiveness of mediating effect test results, this paper makes Sobel test and bootstrap test. The results show that the robust standard error of Sobel test is 0.0082, and the test p value is less than 0.05, indicating that the mediating effect is tenable. Using bootstrap test, the sampling number is set to 500, the robust standard error is 0.0131, the test p value is less than 0.05, the confidence interval is [0.3280,0.3793], and the confidence interval does not contain 0, which indicates that the mediating effect of the model exists again.

Following the steps of mediating effect test (Table 6), the study finds that environmental regulation has a significant positive impact on green innovation (β= 0907, $P < 0.001$, Model 1). Every 1% increase in environmental regulation, 0.0238% increase in human capital and 0.182% increase in green innovation (β= 0238, $P < 0.001$, Model 2; β= 182, $P < 0.001$, Model 3). The mediating effect accounted for 4.7757%, which verified hypothesis H4. The formulation of environmental regulation will significantly improve the level of human capital, and the improvement of human capital has a significant positive impact on green innovation. It shows that human capital plays an important role in this process. Under the condition of stricter environmental regulation, producers tend to pay more attention to the cultivation of green innovative talents and encourage talents with high green innovation potential. The improvement of human capital brings new knowledge and new technology to green innovation activities, and is conducive to improving the level of green innovation (Song et al, 2021).

Table 6: Mediating effect test results

Variable	*lnGI*	*lnEdu*	*lnGI*
	(1)	(2)	(3)
L.lnGI	0.735***		0.708***
	(0.0115)		(0.0118)
lnREG	0.0907***	0.0238***	0.0699***
	(0.00989)	(0.00637)	(0.00980)
lnCity	0.600***	0.0116	0.570***
	(0.202)	(0.0610)	(0.193)
lnInstra	0.449***	0.0446**	0.391***
	(0.0311)	(0.0208)	(0.0325)

lnFdi	-0.0711*** (0.0159)	0.00266 (0.00826)	-0.0775*** (0.0160)
lnFin	0.266*** (0.0200)	0.00308 (0.0109)	0.287*** (0.0206)
L.lnEdu		0.770*** (0.0274)	
lnEdu			0.182*** (0.0246)
Constant	YES	YES	YES
Urban fixed	YES	YES	YES
Year fixed	YES	YES	YES
Observations	5,415	5,415	5,415
Number of id	285	285	285
R-squared	0.882	0.831	0.884
Sobel test		0.2033*** （0.0082）	
_bs_2		0.3536*** （0.0131）	

Note: In parentheses denote the standard error of the respective coefficients, ***/**/* indicates the significance at the 1%/5%/10% levels, respectively.

5.3.Mediating moderating effect test

Table 7 reports the regression results of the regulatory effects of marketization and financial R&D investment. The results show that marketization has a positive impact on green innovation (β= 0687, P < 0.001, Model 1). By introducing the cross product of environmental regulation and marketization (*lnREG×lnMar*), the marketization of regulatory variables has a significant positive effect on green innovation (β= 0295, P < 0.001, Model 2). It shows that when the degree of marketization is high, the promotion of environmental regulation on green innovation is strengthened. On the contrary, it weakens the role of environmental regulation in promoting green innovation. In order to strengthen the role of the market, the guiding opinions on building a market-oriented green technology innovation system issued by the national development and Reform Commission and the Ministry of science and technology clearly states that enterprises must participate in green innovation projects with clear market orientation, and the proportion of green R&D projects supported by major national science and technology projects and national key R&D plans led by enterprises shall not be less than 55%.

Many scholars believe that financial R&D investment crowns out private investment and ignores the important role of public R&D expenditure.In the field of environmental governance and green innovation, financial R&D expenditures crowd out producer investment, which is not conducive to improving the level of green innovation (Chervier, 2019). But is that really the case? The results show that financial R&D investment has a positive impact on green innovation (β= 298, P < 0.001, Model 3). By introducing the cross factor of environmental regulation and financial R&D investment (*lnREG*×*lnPte*), the impact of financial R&D investment on green innovation also has a significant positive regulatory role (β= 0267, P < 0.001, Model 4). It shows that financial R&D investment strengthens the promotion of environmental regulation on green innovation. On the contrary, it weakens the promoting effect of environmental regulation on green innovation and tests hypothesis H5. Financial R&D investment and effective guidance are important ways to improve urban green innovation. In recent years, the Chinese government has provided a lot of R&D subsidies for enterprises, such as purchasing advanced equipment and technology, training R&D personnel for technological transformation.According to the statistics of the National Bureau of statistics from 2016 to 2020, the national financial expenditure on science and technology is 4.12 trillion yuan, with an average annual growth of 10.37%. As a result, major innovative achievements such as Tiangong travel, Mozi communication and C919 aircraft have emerged one after another.

Table 7: Moderating effect test results

Variable	*lnGI*			
	(1)	(2)	(3)	(4)
L.lnGI	0.701***	0.695***	0.585***	0.574***
	(0.0123)	(0.0127)	(0.0168)	(0.0173)
lnEdu	0.169***	0.175***	0.180***	0.187***
	(0.0246)	(0.0251)	(0.0237)	(0.0254)
lnREG	0.0667***	0.0727***	0.0678***	0.0806***
	(0.00995)	(0.0100)	(0.00984)	(0.0107)
lnMar	0.0687***	0.0725***		
	(0.0160)	(0.0161)		
lnREG×*lnMar*		0.0295***		
		(0.00947)		
lnPte			0.298***	0.289***
			(0.0199)	(0.0197)
lnREG×*lnPte*				0.0267***
				(0.00729)
lnCity	0.572***	0.572***	0.496***	0.500***
	(0.191)	(0.190)	(0.182)	(0.186)
lnInstra	0.379***	0.385***	0.389***	0.409***
	(0.0319)	(0.0322)	(0.0348)	(0.0358)
lnFdi	-0.0823***	-0.0772***	-0.0891***	-0.0794***
	(0.0165)	(0.0162)	(0.0181)	(0.0178)
lnFin	0.288***	0.275***	0.245***	0.244***

	(0.0207)	(0.0204)	(0.0213)	(0.0214)
Constant	YES	YES	YES	YES
Urban fixed	YES	YES	YES	YES
Year fixed	YES	YES	YES	YES
Observations	5,415	5,415	5,415	5,415
Number of id	285	285	285	285
R-squared	0.885	0.885	0.894	0.894

Note: In parentheses denote the standard error of the respective coefficients, ***/**/* indicates the significance at the 1%/5%/10% levels, respectively.

6. Conclusion and Policy Implications

The core of green innovation is to promote resource conservation and governance, environmental friendliness and governance. Environmental regulation has become an important means to promote green innovation. This study has important theoretical value and practical significance for clarifying the relationship between environmental regulation and green innovation, and promoting pollution control and environmental protection from the perspective of green innovation.

Based on the panel data of 285 prefecture level cities in China from 2000 to 2019, this paper theoretically and empirically analyzes the impact of China's urban environmental regulation on green innovation. The results show that environmental regulation has a significant and sustained positive impact on green innovation, which falsifies the "Restriction Theory". The strong and weak zoning of environmental regulation fails to reflect the direction of policy implementation, and the strong and weak zoning of green innovation has guiding significance for policy implementation. Specifically, strong green innovation city is suitable to improve the intensity of environmental regulation, and innovation compensation effect is significant. Weak green innovation cities can not formulate policies with high regulation intensity, and the crowding out effect of compliance cost is obvious.

Under the circumstance of stricter environmental regulations, producers pay more attention to the promotion and accumulation of human capital, which provides strong intellectual support for green innovation activities. The relationship between the marketization of regulatory variables and government research investment on green innovation has a significant positive strengthening regulatory role. It shows that the promotion of environmental regulation on green innovation is strengthened when marketization and government investment in scientific research are high. On the contrary, it weakens the role of environmental regulation in promoting green innovation.

We use SYS-GMM model, and select the explained variable of lag period, the mean value of environmental regulation and air circulation coefficient as the instrumental variables. After reducing the endogeneity of the model, improving the intensity of environmental regulation can still promote the level of green innovation. Using the spatial Durbin decomposition model, we find that environmental regulation has spatial spillover effect on green innovation. The formulation of environmental regulation strategy has gradually changed into "Top To Top Competition", which is conducive to the coordinated development of regional green innovation.

Based on the above research results, this paper puts forward the following policy recommendations: First, environmental policy needs to be adapted to local conditions, step by step.The implementation of environmental regulation policy needs to comprehensively consider the local reality. According to the urban development model, resource endowment and location characteristics, take reasonable and appropriate environmental regulation policies according to local conditions. Optimize the compound environmental policy and encourage the public to actively participate in ecological and environmental protection activities.

Second, cultivate green human capital and stimulate the vitality of green innovation. Strengthen the top-level design of green human capital management, and pay attention to the balanced development of green human capital segmentation. In the recruitment and selection process, priority should be given to employees with environmental awareness, and training on environmental management knowledge and skills should be strengthened. Relying on digital technology to optimize the management system, improve the efficiency of green human capital allocation mechanism.

Third, the combination of efficient market and promising government. We need to give full play to the role of market mechanism, innovate the supply and demand mechanism of green technology, and enhance the market value of green technology.The government should increase the R&D investment support for green key technology, explore the transfer and benefit distribution mechanism of funded achievements projects to inventors and small and medium-sized enterprises, and strengthen the innovation guiding leverage of financial R&D investment.

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Author Contribution

Weiyong Zou - Conceptualization, Methodology, Writing-original dra, Data collection and Data curation, Software, Formal analysis, Visualization; Validation; **Yunjun Xiong -** Data curation, Resources, Funding acquisition, Supervision.

Consent to participate

Not applicable.

Consent to publish

Not applicable.

Compliance with ethical standards

We strictly abide by ethical standards.

Data availability

The datasets used during the current study are available from the corresponding author on reasonable request.

Declaration of Conflicting Interests

The author(s) declare that there are no potential conflicts of interest related to the research, authorship, and/or publication of this article.

Ethical approval

No animal or human parts were used in this study.

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