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The intermediary and threshold effect of green innovation in the impact of environmental regulation on economic Growth: Evidence from China

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A R T I C L E I N F O

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A B S T R A C T

Behind the rapid economic growth, the problems of environmental pollution have gradually become prominent. Environmental regulation is an important means for the government to deal with environmental problems in economic development and promote the construction of ecological civilization. Using the provincial data of China from 2005 to 2020, this paper studies the intermediary effect and threshold effect of green innovation in the process of environmental regulation affecting economic growth. The stepwise regression model of intermediary effect shows that environmental regulation promotes green innovation significantly, which further promotes economic growth. The panel threshold regression model shows that when green innovation is below 7.984 (the second threshold), environmental regulation positively affects economic growth, and when green innovation exceeds the second threshold, their marginal effects weaken. Further research shows that there is the regional specific heterogeneity effect. This paper analysis from 4 regions of China. When green innovation exceeds a certain threshold (eastern threshold is 4.382, central threshold is 6.553, western threshold is 5.037, northeastern threshold is 5.347), it decreases the marginal impact effect each region. The research results can provide reference for the government to formulate reasonable policies to balance environment and economy.

1. Introduction

Economic growth is accompanied by environmental pollution problems usually, and environmental protection has received widespread attention. China's booming economy relies heavily on the traditional industrial model (Wang and Wang, 2011). Serious environmental pollution is the inevitable consequence of extensive economic development, and its harm to society is gradually revealed. It is no longer feasible to rely on excessive consumption of the environment to develop economy, and China's environmental problems have begun to become one of the key factors restricting economic development. While cheering rapid growth of the economy, we also need to focus on ecological environmental protection. Nowadays, there is a contradiction between the people's ever-growing need for a better life and unbalanced and inadequate development, and a beautiful environment is the cornerstone of a well-being life for all people. The 18th National People's Congress of the Communist Party of China emphasized ecological civilization construction should be placed in a more prominent position, and put forward the great idea of "Lucid waters and lush mountains are invaluable assets". China economy has officially entered the stage of green development.

China's environmental protection publicity starts late, people's environmental awareness is not enough, enterprises did not take the initiative to protect the environment into the focus of enterprise production, which requires the government to adopt environmental regulations to restrict. The government has promulgated many regulations and laws related to environmental protection over recent years. For example, the Environmental Protection Law of the PRC was reformed in 2014, the Environmental Protection Tax Law was promulgated in 2016, the Yangtze River Protection Law and the Resource Tax Law were passed in 2020, the government is expressing its determination to manage the environment with practical actions. In 2021, the "3060 target" was proposed in the government work report, hoping to achieve "carbon peaking" and "carbon neutrality" at an early date. The Chinese government is constantly strengthening environmental protection, striving to improve environmental quality, hoping to promote upgrading and transformation of industrial structure, alter the traditional mode of economic growth, and promote better and faster economic development through environmental governance.

Environmental regulation is one of better environmental policy instruments (Wang and Zhang, 2022). Reducing environmental pollution can ameliorate the quality of economic development (Liu and Liu,

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2021). How to promote economy and solve environmental problems is worth discussing. Ways to drive economic growth by investing a lot of labor and money should be abandoned. Technological innovation has always been a key driver for promoting high-quality and sustainable development of economy and society. For a long time, the environment and economy have formed a strange circle of trade-offs. Technological innovation, especially green innovation, has become a link to balance economic growth and environmental protection (Pelin and Effie, 2011). The Porter theories believes environmental regulation helps to promote science and technological innovation. Simultaneously, innovation promotes the benign development of society and economic growth. Enterprises increase investments in R&D and technological transformation to cope with the "forced mechanism" of environmental regulation. (Wu et al.,2021). However, environmental regulations may be too strict to stimulate enterprises' technological innovation. Therefore, technological innovation may affect the degree and direction of correlation between environmental regulation and economic growth.

Although classical economic theory, Porter theory and related research have covered the relevance between environmental regulation and economic growth, these studies generally lose sight of the indirect impact of green innovation on it, especially the threshold and linkage effect of green innovation have not been paid attention to. We have three questions: Firstly, does China's environmental regulations continuously promoted economic growth? Secondly, is there a transmission relationship between them through green innovation? Thirdly, what are the temporal and regional characteristics of the two under different quantities of green innovation? Studying these issues can explore the intrinsic relevance among environmental regulation, green innovation and economic growth, and help government to formulate reasonable environmental policies, which is very significant for the transition of social economy to high-quality and sustainable development. Taking strengthening environmental protection and promoting economic growth as main line, I deeply explore the transmission relationship and mechanism among environmental regulation, green innovation and economic growth from 2005 to 2020.

The remainder of the study is arranged below. Section 2 provides literature review, Section 3 introduces theoretical mechanism and proposes four research assumptions. Section 4 gives a list of methods and data. Section 5 and section 6 analyze and discuss the empirical results. Finally, in section 7, I draw some conclusions and policy implications.

2. Literature review

There is no consistent view on how environmental regulations affect economy. Some studies have attempted to explain the beneficial impact. After the introduction of environmental tax policies, Romania has also reduced environmental pollution, accelerated regional economic growth, and achieved a double dividend (Andrei et al., 2016). Environmental regulation can improve production efficiency, enhance enterprises profitability and competitiveness (De Santis et al., 2021; Wang and Zhang, 2022), not only achieve their direct purpose of energy conservation and emission reduction, but also promote economic growth (He and An, 2019; Qian et al., 2019). Under the synergistic effect of high-tech industrial agglomeration, this impact is more significant (Jiang and Tan, 2021; Su et al., 2020; Meng and Shao, 2020). Environmental management can significantly improve the optimal growth rate and environmental carrying capacity (Huang and Lin,2013; Xu et al., 2020), and the government's smog and haze control policies can help improve the atmospheric environment, thereby improving the economic development quality and promoting sustainable economic growth (Chen and Chen, 2018). Measuring environmental regulation policies with sulfur dioxide emissions trading (Cheng and Fu, 2020) or reasonable government compensation rates and environmental taxes (Fan, 2018), it is found that they can not only maintain stable economic growth and improve income distribution pattern, but also improve environmental quality. Zhao and Wang (2017) divided environmental regulation into formal and informal. Formal regulation performs positively influences on economic development, and the promoting effect of informal regulation on industrial development has gradually emerged. Huang and Gao (2016) conducted empirical research from the dual perspectives of quality and quantity of economy, pointing out that environmental regulation promotes economic growth quality, but worsens the inhibition effect on economic growth quantity. Environmental regulation increases the production costs incurred by the initial costs that society must bear in a short time, but they can promote tech-innovation and increase long-term investment opportunities for sustainable economic growth (Liang et al., 2022; Tang et al., 2019). Li and Shen (2019) argued that environmental regulation can significantly improve new urbanization level of the local and surrounding cities.

Some studies have evidence that environmental regulation hinders economic growth. It is possible that the profits gained from technology patents may not bring excess returns to the enterprises because of environmental regulation. Therefore, when enterprises are subject to environmental regulation, they will increase a part of their costs to comply with the system. The economic burden and cost pressure of enterprises increase, and the negative impact of corporate performance is greater (Krautzberger and Wetzel, 2012; Levinsohn and Petrin, 2000), thereby hindering business development (Chintrakarn, 2008). At present, the pollution control costs are too high in China, environmental regulation will reduce corporate profits and constrain economic growth (Xie and Liu, 2019). Industrial total factor productivity declines gradually along with the strengthening of environmental regulation (Hille and Möbius,2018; Li and Wei, 2014; Greenstone et al., 2012). Due to the need to increase the expenditure on pollution control and make up for profit gaps, some enterprises will instead accelerate polluting industries operation, and the relevant regulations have a time lag, which does not actually achieve the role of pollution reduction (Huang et al., 2018). Strict enforcement of environmental regulations may lead to enterprises migrating to less intensive areas, reducing urban productivity (Jin and Shen, 2018). As local governments compete for GDP growth, environmental regulations may not be fully implemented, which leads to the failure to promote regional industry upgrading (Lin and Guan,2020). Due to a lack of coordination between local governments, environmental regulations in neighboring areas interfere with each other, resulting in local environmental regulations constraining economic competitiveness (Zhou and Han, 2020). The new environmental regulations are positively affecting the low-level economic development (Wang et al., 2022). In order to cope with environmental supervision, enterprises increase pollution control cost, which negatively impacts technological innovation and extended reproduction (Wang and Zhang, 2022). The above series of reasons prove the hindering role of environmental regulation on economic growth.

Scholars also examined the heterogeneity of them, arguing that it cannot simply be expressed in terms of promotion or inhibition. Du et al. (2021) found the influence of environmental regulation on cost reduction varies by the time period and industry. Environmental regulations reduce production efficiency and inhibit economic growth in the short run, while they improve productivity and accelerate economy in the long run (Lanoie et al., 2008). Their intensity increases from east to west in space, and the impact on green economy efficiency presents a tendency of first promoting and then restraining (Qi and Chen, 2018). Environmental regulation in developed regions can promote economic growth, while environmental regulation in developing regions can adversely affect economic growth (Lin et al., 2015). Under the influence of advanced technology, the economy of eastern China is actively affected by environmental regulations; while because of lacking of advanced environmental protection technologies, the central region as well as western is less affected by environmental regulations (Song and Wang, 2013). China's environmental regulation promotes the quality of economic growth in the east, but constrains the quantity of economic growth in the central and western regions (Huang and Gao, 2016). Liu and Xue (2021) established a nonlinear model of environmental regulation and found it has "U" shaped characteristics for high-quality economic development, the reason may lie in the dynamic equilibrium between the two (Xie et al., 2017; Li and Wang, 2019), or different types of environmental regulation (Tu et al., 2019; Sun et al., 2019; Wang and Zhang, 2022).

Many scholars have noted the linkage role of technological innovation when probing into the relevance of environmental regulation on economic growth (Song and Wang, 2013). However, as far as we know, few studies have attempted to explore the intrinsic relationship between the three. There are not many people who truly incorporate green innovation into the system model, we can only infer the potential impact mechanism among the three through other relevant studies. Daniela and Marco (2022) suggested Italian policymakers should concentrate on novel green technologies and encourage investments in green technologies to promote sustainable growth. Zhang et al. (2011) and Huang and Hu (2010) conducted an empirical study of enterprises to test the relationship of environmental regulation and technological progress, the results show that environmental regulation promotes technological innovation coordinately. Zhang et al. (2019) verified that utility model patents and green patents significantly improve economic growth. In the process of environmental regulation affecting economic growth, whether green innovation plays a conductive intermediary effect? Whether it is an impact threshold? Whether there are different regional characteristics in eastern, western, central, and northeastern China? These questions have not been really solved in the existing literature.

This study makes the following contributions. Firstly, environmental regulation, green innovation and economic growth are put into the same framework for analysis, and the research conclusions are helpful to understand the internal mechanism of environmental regulation on economic growth. Secondly, it is helpful to have more comprehensive understanding of their mechanism by studying the mediating role of green innovation. Thirdly, green innovation is incorporated into the nonlinear model, the temporal and regional characteristics of environmental regulation on economic growth under different technological innovation conditions are analyzed.

3. Theoretical analysis and hypotheses

This paper focus on the intermediate and nonlinear mechanism and regional heterogeneity of the environmental regulation on economic growth.

3.1. Direct and intermediate influences

As a policy tool, environmental regulation promotes comprehensive ecological improvement by drawing up and implementing environmental policy with the leading forces of the government. (Li et al., 2021a;). Both Porter hypothesis and neoclassical growth theory have clarified their impact. Strict environmental regulations can actually improve competitiveness (Porter and Linde, 1995). Porter hypothesis believes that enterprises can benefit from elaborately formulated environmental regulations, because reasonably designed environmental cleaning standards can stimulate innovation, reduce pollution and improve the productivity of resource use at the same time, which can fully or partially counteract the cost of obeying these standards. According to the new classical growth theory, the environmental governance is not friendly to promoting economic growth because it raises enterprises' production cost and reduces innovation investment (Langpap and Shimshack, 2010). Although they have opposite views, they both express that economic growth is related to environmental regulation. The support of Chinese government has played a great role. First of all, the environmental supervision policies carried out by the regulating authority set production and emission standards for enterprises with high pollution emissions, enterprises cut down the consumption of corresponding polluting energy because of increasing in production costs. Meanwhile, the government subsidizes the production and use of clean energy from the demand side, which also reduces the consumption of highly polluting energy, and tries to reduce enterprises' burden, so as to reduce the unexpected output during economic development. Second, the transfer of enterprises in different regions caused by environmental regulations can promote economic growth. Due to different regional environment and economic development, various types of enterprises may adopt different ways to respond to environmental regulation policies. Environmental regulation may further stimulate the innovative power of high-tech enterprises, but it may also lead some highly polluting industrial enterprises to seek development in areas with low environmental regulation intensity. These areas usually have underdeveloped economies. The transfer of industries can drive the employment and income growth of local residents, and then promoting economic growth (Xu et al., 2020).

Hence, I propose hypothesis 1: Environmental regulation has a direct and positive influence on economic growth.

Implementing environmental regulations can improve green innovation capability. Green innovation is a revolutionary of environmental protection technology (Liu and Li, 2022), reasonable intensity of environmental regulation can eliminate enterprises' fluke mentality of avoiding environmental regulation costs, and then stimulate enterprises to make full use of resource factors, increase R&D investment and upgrade green production technology (Xu et al., 2020), When confronting increasingly stringent environmental regulations, enterprises only choose green innovate to offset environmental costs and increase profitability, which naturally stimulates the increase in green innovation. For the sake of improving environmental protection level, the government adopt a subsidy policy for enterprises' green technology, which is advantageous to alleviating enterprises' financial pressure for ecological protection and improving their green technology innovation capabilities (Lu and Zheng, 2022). Technology coefficients are considered into the Robert model, Huang and Liu (2006) found that environmental governance increases the cost of enterprises, as well as stimulates tech-innovation to a certain degree. (Cao et al., 2020; Cao and You, 2017; Klemetsen et al., 2018) have studied and proved that environmental regulation stimulates innovation.

Technological innovation is one of the important sources of economic growth (Batabyal and Beladi, 2014; Colino et al., 2014). Romer's "Endogenous Growth Theory" explored how technological progress affects economic growth. Lucchess (2011) took Germany and other six countries as examples, and found that the importance of technological innovation in industrial structure and economic growth. Yue et al. (2022) believed that China should focus on promoting green innovation, relying on innovative industries to drive industrial structure optimization, and enhance national competitiveness, and promote green economy growth. Green innovation can drive the mechanization and intelligence of the production process, reduce environmental pollution costs and human resources costs. The production efficiency and profit margin of enterprises are improved, the market competitiveness of enterprises is enhanced, market share is expanded, economic benefits of enterprises are improved, so as to achieve economic growth.

Strict environmental regulation can not only significantly change division of labor in technology innovation, but also promote economic growth (Tang et al., 2019), and environmental regulation can improve regional high quality economic development by stimulating technology (Yin and Liu, 2018). Therefore, I propose hypothesis 2: environmental regulation indirectly affect economic growth through green innovation.

3.2. Nonlinear effects

In pace with environmental regulations, enterprises are more willing to choose green innovative technologies for production in order not to pay more production costs. The use of green technology will enable enterprises to reduce pollution control costs, improve enterprise production efficiency, and bring new vitality and stronger competitiveness to enterprises. And this healthy competition also brings vitality to

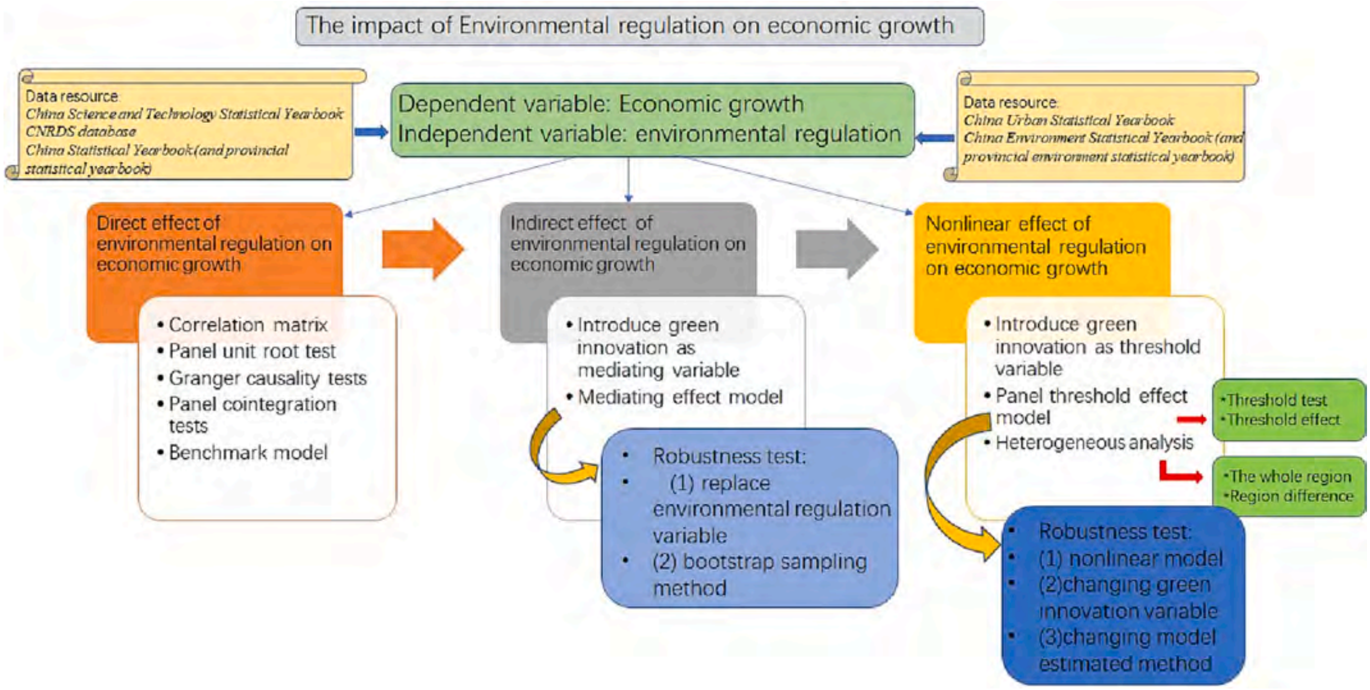

Fig. 1. The methodological framework.

economy, impels the vigorous development of market. Under the government's encouragement of independent innovation and the constraints of environmental regulations, enterprises are more willing to carry on appropriate amount of green innovation to meet environmental regulatory standards. Through green innovation, enterprises improve production processes, and ultimately promote regional productivity and economic growth.

However, there are accumulation effects and threshold effects in technological innovation (Fang et al., 2022). Once the number of green innovations grows too fast, the funds invested by enterprises in technological innovation activities may not be rewarded. Enterprises' production costs continue to increase with the strengthening of environmental regulations, R&D activities will also be constrained because of a tight budget, the overall competitiveness of enterprises will decline, and profits will decrease, thus adversely affecting economic growth.

Hence, I argue hypothesis 3: Green innovation exhibits a threshold moderating effect on environmental regulation and economic growth, and its marginal effects may be weakening.

It is different that the technological advantages, resource endowments, and economic development of different areas in China, which clearly demonstrates the regional heterogeneity. Applicability of "Porter hypothesis" varies by different regions. Shen and Liu (2012) thought that it was difficult to support it in the backward central and western regions, but it was well supported in the more developed eastern regions. Tao and Peng (2018) discovered the promoting role of innovation drive on economic growth is accelerating in the east, convergent in the middle and differentiative in the west. Not all technological innovations can effectively solve the problem of environmental pollution. The economy in the central and western China is underdeveloped, and the endogenous capacity of industrial enterprises for technological progress is insufficient. Some enterprises mainly rely on simple imitation or technology introduction to produce. They are at the low end of the industrial value chain and consume a great deal of resources in production. Considering the production cost, the new technology introduced by some enterprises is likely to be obsolete in developed areas, which often causes more resource consumption and environmental damage. Moreover, some innovations may only remain at the level of exploration, and play an insufficient role in the end use (Wils, 2001; Czech, 2008).

In view of these, there is the possibility of regional heterogeneity in the influence of environmental regulation on economic growth. By classification of the China Statistical Yearbook, China is divided into eastern, central, western and northeastern regions for analysis. The economic development level and industrial intensity of the four major regions are inconsistent, the economy of central and eastern areas is better than that of the west. There are many heavy industrial enterprises in the northeast. The marginal effect of environmental regulation on economic growth is decreasing due to the different geographical environment and the different quantities of green innovation. The central region needs to carry pollution-intensive enterprises migrated from the east. Although the natural environment in the west is superior and environmental carrying capacity is strong, due to the weak green innovation and application ability, the pollution control costs that enterprises need to pay are increasing with the increase of environmental regulations, and their finances are in trouble, and economic growth has also been involved to some extent. The economy of the northeast region is largely dependent on the development of heavey industries, which has caused prominent environmental problems. After green innovation exceeds a certain threshold, enterprises will bear too much innovation investment, causing a certain blow to enterprises, resulting in adverse impacts of environmental regulation on economic growth. Enterprises' innovation activities cannot be completely transformed into production efficiency, which leads to the situation that innovation achievements cannot bring high profits. In addition, there is the burden of pollution control costs, so enterprises' overall operation has improved, but it is still restrained by environmental regulations.

Therefore, I further propose hypothesis 4: the threshold effects of green innovation between environmental regulation and economic growth are heterogeneous.

4. Methods and data

The research method I used includes three aspects (Fig. 1.): (1) identifying the linear and nonlinear effects; (2) analyzing the indirect effect based on intermediary effect of green innovation; and (3) analyzing the nonlinear relationship based on the threshold effect of

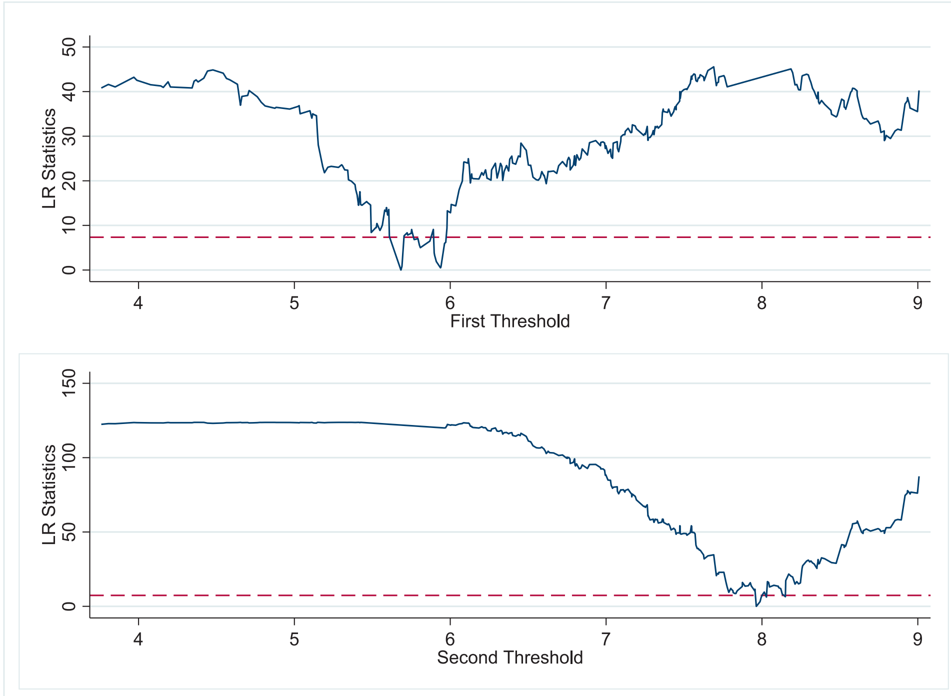

Fig. 2. 5% critical value construction of the thresholds.

green innovation..

4.1. Benchmark model

construct a panel data model with two-way fixed effect as benchmark model, as shown in formula (1).

$$lnPGDP_{i,t} = \beta_0 + \beta_1 lnEnR_{i,t} + \beta_z CV_{i,t} + \mu_i + \delta_t + \varepsilon_{i,t} \quad (1)$$

Where the explanatory variable is $PGDP_{i,t}$, which represents the actual GDP per capita of the ith province in t period. $EnR_{i,t}$ represents the comprehensive level of environmental regulation of the ith province in the t period, and β_1 refers to the estimated coefficient of $EnR_{i,t}$ and $PGDP_{i,t}$. $CV_{i,t}$ is the vector of a group of control variables. μ_i stands for the ith provincial fixed effect. δ_t denotes the tth time-fixed effect, and $\varepsilon_{i,t}$ represents the random error term.

4.2. Mediating effect model

Refer to the practices of Baron and Kenny (1986), Wen et al. (2004) and Hayes (2009). I use the stepwise regression method as shown in formula (2)-(3) to test the intermediary effect. Here, $IN_{i,t}$ represents the mediating variable. To mitigate the effects of heteroscedasticity and multicollinearity, I logarithmize the variables.

$$lnIN_{i,t} = \gamma_0 + \gamma_1 lnEnR_{i,t} + \gamma_2 CV_{i,t} + \mu_i + \delta_t + \varepsilon_{i,t} \quad (2)$$

$$lnPGDP_{i,t} = \vartheta_0 + \vartheta_1 lnER_{i,t} + \vartheta_2 lnIN_{i,t} + \vartheta_3 CV_{i,t} + \mu_i + \delta_t + \varepsilon_{i,t} \quad (3)$$

If the regression coefficients in the above model meet the following conditions simultaneously, I will believe green innovation has intermediary effect between environmental regulation and economic growth. First, the parameter β_1 is significant; Secondly, the parameter γ_1 is significant; Third, the parameter ϑ_2 of green innovation is significant, and $\vartheta_1 < \beta_1$. If the parameter of environmental regulation ϑ_1 pass the significant test, it is a partial intermediary, and if ϑ_1 fails the test, it is fully intermediary.

4.3. Panel threshold model

In order to further consider the nonlinear impact, I add the green innovation $IN_{i,t}$ and the multiplication terms of $EnR_{i,t}$ to formula (1), get formula (4) as follow:

$$lnPGDP_{i,t} = \beta_0 + \beta_1 lnEnR_{i,t} + \beta_2 lnIN_{i,t} + \beta_3 \times lnEnR_{i,t} \times lnIN_{i,t} + \beta_4 \times lnEnR_{i,t} \times lnIN_{i,t}^2 + \beta_z CV_{i,t} + \mu_i + \delta_t + \varepsilon_{i,t} \quad (4)$$

However, it is not easy to judge the nonlinear turning point according to formula (4), so I introduce a panel threshold model. The panel threshold models are more commonly used in macroeconomic and financial analysis, and less researches have used this econometric model in environmental research (Ouyang et al., 2019; Shao and Shen, 2017).

Formula (5) considers the single-threshold model, formula (6) considers the double-threshold model, where τ, τ_1, τ_2 are threshold values of the green innovation, and $I(\bullet)$ stands for the indicative function, $(\bullet)$ represents a condition, if the conditions is satisfied, $I(\bullet) = 1$; otherwise, $I(\bullet) = 0$.

$$lnPGDP_{i,t} = \alpha_0 + \alpha_1 lnEnR_{i,t} \times I(lnIN_{i,t} \le \tau) + \alpha_2 lnEnR_{i,t} \times I(lnIN_{i,t} > \tau) + \alpha_3 CV_{i,t} + \mu_i + \delta_t + \varepsilon_{i,t} \quad (5)$$

$$lnPGDP_{i,t} = \eta_0 + \eta_1 lnEnR_{i,t} \times I(lnIN_{i,t} \le \tau_1) + \eta_2 lnEnR_{i,t} \times I(\tau_1 < lnIN_{i,t} \le \tau_2) + \eta_3 lnEnR_{i,t} \times I(lnIN_{i,t} > \tau_2) + \eta_4 CV_{i,t} + \mu_i + \delta_t + \varepsilon_{i,t} \quad (6)$$

The estimated values of τ, τ_1, τ_2 can be calculated using the ordinary least square method. Taking formula (5) for an example,

Let.

$$\alpha = \begin{bmatrix} \alpha_0 \\ \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{bmatrix}, \quad Z_{i,t}(\tau) = \begin{bmatrix} 1 \\ lnEnR_{i,t} \times I(lnIN_{i,t} \le \tau) \\ lnEnR_{i,t} \times I(lnIN_{i,t} > \tau) \\ CV_{i,t} \end{bmatrix}, lnPGDP'_{i,t} = lnPGDP_{i,t} - \mu_i - \delta_t$$

then

Table 1
Descriptive statistics.

variables	symbol	Definition	Observation	Mean	Std. Deviation	Minimum	Maximum
Dependent variable	*PGDP*	Economic growth	496	41664.33	27691.41	5218	164483.7
Independent variable	*EnR*	environmental regulation	496	1.006	5766.422	0	19.112
Mediator and threshold variables	*IN*	Green innovation	496	3138.813	1.68	2	52,808
Control Variables	*hc*	Human capital	496	0.118	0.083	0.009	0.909
	ur	urbanization	496	0.537	0.150	0.209	0.896
	op	openness	496	0.442	0.508	0.109	0.229
	gov	Government support	496	0.267	0.193	0.092	1.354
	ter	Industry structure	496	0.461	0.098	0.288	0.839

Table 2
Benchmark model results.

	lnPGDP	*lnPGDP*	*lnPGDP*	*lnPGDP*	*lnPGDP*
	(1)	(2)	(3)	(4)	(5)
lnEnR	0.078***	0.053***	0.222***	0.018**	0.012*
	(0.012)	(0.008)	(0.026)	(0.010)	(0.007)
hc				0.432***	0.030**
				(0.039)	(0.018)
ur				1.461***	0.699***
				(0.112)	(0.045)
op				0.053**	0.084***
				(0.026)	(0.011)
gov				0.723***	−0.284***
				(0.071)	(0.0424)
ter				0.206*	−0.725***
				(0.111)	(0.054)
constant	10.499***	9.559***	11.284***	6.985***	8.661***
	(0.029)	(0.075)	(0.123)	(0.532)	(0.274)
Year FE	No	Yes	No	No	Yes
Province FE	No	No	Yes	Yes	Yes
R-square	0.085	0.613	0.487	0.627	0.786
F-statistics	45.79	47.38	14.19	596.59	1307.20

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; Robust standard errors in parentheses.

$$lnPGDP'_{i,t} = \alpha Z_{i,t}(\tau) + \varepsilon_{i,t}$$

$$\widehat{\alpha}(\tau) = \left(Z_{i,t}\tau' Z_{i,t}(\tau)\right)^{-1} Z_{i,t}\tau' \ln PGDP'_{i,t}$$

$$\widehat{\tau} = argminS_n(\tau)$$

Where, $S_n(\tau)$ is the sum of squared residuals. $\widehat{\tau}$ comes from minimizing the value of $S_n(\tau)$. STATA 16.0 software uses a grid search method to minimize $S_n(\tau)$.

4.4. Variables and data sources

In my paper, panel data from 31 provinces (cities and autonomous regions) in China (except Hong Kong, Macao and Taiwan) from 2005 to 2020 were selected for empirical analysis. The raw data for all variables are from *China Science and Technology Statistical Yearbook*, CNRDS database, *China Statistical Yearbook*, *China Urban Statistical Yearbook*, *China Environment Statistical Yearbook*, provincial statistical yearbook and environmental statistics yearbook.

4.4.1. Dependent variable

PGDP: Economic growth. To make economic growth comparable between regions and avoid the influence of price factors, economic growth indicators are measured by real GDP per capita at constant 2005 prices. The data of real GDP per capita and 2005 price index come from *China Statistical Yearbook*.

4.4.2. Independent variables

EnR: Environmental regulation. In the existing researches, there is no fixed measurement indicator for environmental regulation. Whether environmental regulation is command-based, incentive-based, or public participation-based, its ultimate goal is to control the pollution emissions and alleviate environmental pollution problems. In this study I focus on pollution abatement costs. Referring to the practice of Wang and Li (2015), and in view of the comparability and availability of data, first of all, industrial pollution investment and emission of each pollutant were normalized separately, so as to weaken the impact of the quantity unit and dimension of each index. Then, *EnR* is calculated by the treatment input required per unit of pollutant. It is calculated as formula (7). Industrial pollutants mainly select industrial wastewater, industrial sulfur dioxide and industrial smoke (powder). The emissions of these three pollutants are representative. This measure method has been used in many papers (Zhang et al., 2021; Li et al. 2022).

$$EnR_{i,t} = \frac{1}{3}\sum_{j=1}^{3} \frac{y_{i,t}/po_{j,i,t}}{\sum_{i=1}^{31}\frac{y_{i,t}}{po_{j,i,t}}\Big/31} \quad (7)$$

where subscript *j* refers to different pollutants. *y* stands for the total amount of industrial pollution investment, *po* is the amount of pollutant discharged, the larger *EnR* is, the greater the intensity of environmental regulation. The data of *y* is from *China Statistical Yearbook*, and the data of pollutant discharged of industrial wastewater, sulfur dioxide and smoke are from *China Environment Statistical Yearbook*, and provincial environmental statistics yearbook.

4.4.3. Mediating variable and threshold variable

According to the foregoing mechanism analysis, environmental regulation, green innovation and economic growth are closely related, the influence degree varies at different level of green innovation. Therefore, green innovation is both the mediating and threshold variable. I choose the quantity of green patents granted from *China Science and Technology Statistical Yearbook* to measure green innovation.

4.4.4. Control variables

(1) Human capital (*hc*). Ratio of the number of junior college or above to population aged 6 and over is taken to measure human capital levels. (2) Urbanization (*ur*). Ratio of urban permanent population to total population is used. (3) Government support (*gov*). The proportion of fiscal expenditure to GDP is used. (4) Openness (*open*). The proportion of total imports and exports to GDP is adopted to measure openness (Ma and Zhu, 2022; Antweiler et al., 2001). (5) Industrial structure (*ter*). It is represented by the ratio of the added value of tertiary industry to that of GDP. *hc, gov, ter* come from *China Statistical Yearbook*, *open* is from CNRDS database, and *ur* comes from *China Urban Statistical Yearbook*.

4.5. Descriptive statistics and panel causality tests

Table 1 shows descriptive statistics, and Appendix Table A1 lists variables' and terms' abbreviation. I used correlation tests, panel unit root tests, Dumitrescu and Hurlin (2012) Granger causality tests, and panel cointegration tests to observe the causality among variables. The correlation matrix and test (Appendix Table A2) shows that all variables have significant correlation at a significance level of 5%. Appendix Table A3 demonstrates that all variables are stable and have a 0-order cointegration relationship. Dumitrescu and Hurlin (2012) Granger causality test statistics are significant at the 5% significance level,

Table 3
mediating effect.

	lnPGDP	*lnIN*	*lnPGDP*
	(1)	(2)	(3)
lnEnR	0.012***	0.047***	0.002
	(0.007)	(0.023)	(0.006)
lnIN			0.335***
			(0.013)
constant	5.904***	1.464	6.494***
	(0.209)	(1.222)	(0.341)
Control variables	yes	yes	yes
Province FE	yes	yes	yes
Year FE	yes	yes	yes
R-squared	0.786	0.176	0.828
F-statistic	1307.20	610.81	1347.23

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; Robust standard errors in parentheses.

Table 4
Robustness test.

	lnPGDP	*lnIN*	*lnPGDP*
	(1)	(2)	(3)
ln*er1*	0.175***	0.380***	0.079***
	(0.009	(0.022)	(0.009)
ln*IN*			0.251***
			(0.015)
constant	7.7286***	1.734***	7.293***
	(0.478)	(1.154)	(0.038)
Control variables	yes	yes	yes
Province FE	yes	yes	yes
Year FE	yes	yes	yes
R-squared	0.744	0.280	0.878
F-statistic	1122.97	1038.76	1554.11

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; Robust standard errors in parentheses.

Table 5
Threshold effect.

Variables	ln*PGDP*
$\ln ER(\ln IN \leq 5.684)$	0.077***
	(0.014)
$\ln ER(5.684 < \ln IN \leq 7.964)$	0.035***
	(0.012)
$\ln ER(\ln IN > 7.964)$	−0.031***
	(0.014)
Control variables	Yes
Province FE	Yes
Year FE	Yes
Observations	496
R-squared	0.733
F-statistic	590.84

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; Robust standard errors in parentheses.

indicating a two-way or one-way causal relationship between economic growth, green innovation, and environmental regulation (Appendix Table A4). Appendix Table A5 demonstrates the results of the Kao test and the Pedroni test for panel data cointegration testing. Its' original hypothesis is: No cointegration. The test results indicate that at a significance level of 5%, there is a long-term cointegration relationship between variables. We can use these data to establish a panel regression model.

5. Results

5.1. Benchmark model

As shown in Table 2, when province effect, year effect or control variable are considered in the model respectively, the regression coefficient of environmental regulation on economic growth is positive at the significant level of 1%, which hints that environmental regulation can significantly promote economic growth. In order to overcome the heteroscedasticity problem of the residual term of the regression model, I used the robust standard error to construct test statistics. Table 2 also shows that all models have passed the F-test, R square test and *t* test. The regression results support the research hypothesis 1.

5.2. Mediating effects results

Column (1)-(3) in Table 3 lists the stepwise regression results. In Column (1) and Column (2), the coefficients of *lnEnR* are significant at level of 1%, clearly demonstrates that *lnEnR* promotes both green innovation and economic growth. In Column (3), the coefficient of *lnIN* is significant, but *lnEnR* is not, and it is lower than the coefficient of column (1), which reveals that green innovation presents complete mediating effect. The above results verify the research hypothesis 2.

Next, the substitution of mediation variables and bootstrap sampling methods are used for testing the robustness of mediation effects (Ma and Zhu, 2022; Hayes, 2009). Following Chen and Chen (2018), I use the pollution control amount per unit of sulfur dioxide emissions (ln*er*1) as another proxy variable for environmental regulation, re-estimate the formula (2) - formula (3), Table 4 demonstrates the regression results. The influence coefficient of ln*er*1 on economic growth was significantly positive, *lner*1 has significantly promoting effects on technological innovation, and green innovation also has a significantly promoting effects on economic growth. The bootstrap test results for mediation effects are shown in Appendix Table A6. It demonstrates the indirect effects of green innovation is not zero at the significance level of 5%. These verify that the environmental regulation can promote the economic growth through green innovation. The econometric model results are consistent with Table 3, they remain robust, hypothesis 2 is validated.

5.3. Nonlinear effect

Green innovation has a complete mediating effect, indicating that it may have a nonlinear threshold effect between environmental regulation and economic growth. Panel threshold regression model can be considered. Firstly, green innovation is set as a threshold variable, the existence and quantity of thresholds are checked. Secondly, the threshold confidence intervals are determined. Finally, the coefficients for the threshold parameters are calculated. In my paper, the grid points are set to 400 and the 1000 replications for the bootstrap test are used. Appendix Table A7 displays the test of the threshold effects. As shown, the first threshold value of green innovation is 5.684 and the second threshold value is 7.964, which are located in their 95% confidence intervals (5.611, 5.690) and (7.955, 7.976) respectively.

Fig. 2 plots the LR statistic of the threshold estimate to depict the effectiveness of the threshold value. The dashed line in the figure represents the 5% critical value (7.35). I observe the likelihood ratios at 5.684 and 7.964 reach minimum at the 5% level. The confidence interval confirms the correct identification of the double threshold model of green innovation as a threshold variable.

Table 5 presents the threshold regression results with green innovation as threshold variables. When green innovation is lower than the first threshold, $\theta_1 = 0.077, p < 0.01$, which indicates that the coefficient is positive and significant, the growth of environmental regulations per unit can promote economic growth by 7.7%. When green innovation is between the first and second thresholds, $\theta_2 = 0.035, p < 0.01$, the coefficient of environmental regulation is still positive, but the effect is weakened. Once green innovation exceeds the second threshold, the impact turns to negative, $\theta_3 = -0.031, p < 0.01$. These coefficients indicate that economic growth will benefit from the moderate improvement of green innovation, but if it exceeds the threshold, economic growth may be restrained. The results confirm the nonlinear moderating role of green innovation, the marginal effect gradually

Table 6
Threshold effect for 4 regions.

Variables	Eastern China ln*PGDP* (1)	ln*PGDP* (2)	Central China ln*PGDP* (1)	ln*PGDP* (2)	Western China ln*PGDP* (1)	ln*PGDP* (2)	Northeastern China ln*PGDP* (1)	ln*PGDP* (2)
Threshold	$\ln IN \leq 4.382$	$\ln IN > 4.382$	$\ln IN \leq 6.552$	$\ln IN > 6.552$	$\ln IN \leq 5.037$	$\ln IN > 5.037$	$\ln IN \leq 5.347$	$\ln IN > 5.347$
ln*ER*	0.058***	0.002	0.054***	0.016	−0.023***	−0.010	0.039*	−0.011
	(0.000)	(0.008)	(0.002)	(0.017)	(0.007)	(0.006)	(0.023)	(0.024)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	7	153	58	38	53	139	3	45
R-squared	0.696	0.9716	0.769	0.845				
F-statistic	400.29	415.83	1872.9	217.63				

Note: Robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

weakens, which supports hypothesis 3.

5.4. Heterogeneous effects

I further studied the effects of heterogeneity.This subsection examines the nonlinear effects of *lnEnR* on *lnPGDP* in different parts of China, with green innovation as threshold variables. The provincal observations from eastern, central, western and northestern China are used to create four subsamples for the study.

Table A8 displays the threshold test results for each region. Green innovation has passed the single threshold test in all four regions. Further comparison shows that the central region's value of green innovation is larger than other regions, which indicats the threshold in central region is higher(threshold value = 6.553), while the threshold of the eastern region is the lowest (threshold value = 4.382).

The threshold regression by region is shown in Table 6. The same characteristics of all regions are: on the whole, when green innovation is below the threshold, *lnEnR* has a significant influence on *lnPGDP*. when green innovation is above the threshold value, the effect in the eastern and central regions is significantly weakened and not significant, while the inhibition effect in the western region and northeast region is obvious. The above results indicate the impact of environmental regulation on economic growth in China exists regional heterogeneity and green innovation threshold effect. Research hypothesis 4 is validated.

5.5. Robustness test for nonlinear effect

Firstly, I test the robustness of the nonlinear effects using the preceding formula (4). I employ system-GMM model to solve dynamic endogeneity. The first column of Table 7 presents the test results. AR(1) passes the statistical test, indicating sys-GMM estimations are appropriate. The results also show the impact of *lnEnR* on *lnPGDP* is significant and positive, but the estimator of the interaction between *lnEnR* and *lnIN* are significantly negative. It demonstrates that the expansion of green innovation will decline the positive effect of *lnEnR* on *lnPGDP*.

Secondly, I replaced the measurement variable of green innovation. The results with the number of green utility patents granted are shown in column (2) of Table 7, indicate the threshold effect of green innovation still exists significantly. When technological innovation is below the threshold of 5.553, the impact coefficient of *lnEnR* on *lnPGDP* is 0.079. This states that the promoting effect is significant. When green innovation is between 5.553 and 7.705, the promoting effect continues to be maintained, but the slope has decreased. When green innovation exceeds the threshold estimates of 7.705, the impact coefficient changes from positive to negative. These presents that China's environmental regulation inhibits economic growth when green innovation is high. Robustness test results are the same as before.

Thirdly, I construct another balanced panel from 2005 to 2019 for my estimation. the results are shown in column (3) of Table 7, showing no difference with my previous finds too.

As I expected, there was no sharp change in impact direction and significance of the regression coefficients after changing indicator variables, or changing empirical model, or considering alternative time periods, and hypothesis 3 is confirmed again.

6. Discussion

The first goal of my research is to analysis the impact of environmental regulation on economic growth. Consistent with previous conclusions (Berman and Bui, 2001; Murshed et al., 2021; Tang et al., 2019; Wang et al., 2022), my findings indicate that environmental regulation has a important positive impact on economic growth. In the meantime, I have also made new discoveries, and made some contributions to economic growth issues study. I find that when green innovation is included in the research framework, the impact of environmental regulation is non-linear. Environmental regulation affects economic growth through green innovation, and when green innovation is at a low threshold level, the marginal effect of environmental regulation is greater, while when green innovation is at a high threshold level, the marginal effect decreases.

The results in Table 2 present that environmental regulation have a promoting effect on economic growth. However, scholars have also studied the nonlinear relationship between them. Zhou and Feng (2017) considered that there is panel dynamic nonlinear relationship between energy consumption and environmental regulation. Cao et al. (2020) suggested that there is an inverted U-shaped relationship in the Yangtze River Delta region. Song et al. (2021) discover that the relationship curve between the two is an inverted U-shaped using 2004–2017 provincial panel data. From these we can seen that the impact of both is far from linear. As I showed in column (1) of Table 7, when I further introduce green innovation variable (*lnIN*), the interaction of green innovation and environmental regulation ($lnEnR \times lnIN$), and the interaction of $lnEnR \times lnIN^2$ into model (1), the impact effect remains significant. That is, green innovation may be an important influencing factor in the non-linear relationship.

The implementation of environmental regulations can improve social green innovation capabilities (William and Wang, 2022). When faced with increasingly stringent environmental regulations, enterprises choose to offset environmental costs and enhance their own profits via green innovation (Liu and Li, 2022). The results in Table 3 verify the intermediary effect of green innovation, namely green innovation plays an indirect promoting role in the process of environmental regulation on economic growth. When considering green innovation's intermediary role, the coefficient of environmental regulation on economic growth is lower than when it is not considered, indicating that green innovation's intermediary role is significant. In the long run, high pollution production is not feasible, which is not advantageous to the benign development of enterprises, nor does it comply with sustainable development. Enterprises have begun to actively seek technological innovation to promote cleaner and environmentally friendly production environments

Table 7
Robustness check for nonlinear effect.

Variables	ln*PGDP* (1)	ln*PGDP* (2) ln*EnR*(ln*IN* ≤ 5.553)	ln*EnR*(5.553 < ln*IN* ≤ 7.705)	ln*EnR*(ln*IN* > 7.705)	ln*PGDP* (3) ln*EnR*(ln*IN* ≤ 5.940)	ln*EnR*(5.940 < ln*IN* ≤ 7.964)	ln*EnR*(ln*IN* > 7.964)
L. ln*PGDP*	0.727***						
	(0.025)						
ln*EnR*	0.0243**	0.079***	0.034***	−0.032***	0.074***	0.032***	−0.032***
	(0.011)	(0.014)	(0.012)	(0.013)	(0.014)	(0.012)	(0.013)
ln*IN*	−0.022**						
	(0.009)						
ln*EnR**ln*IN*	−0.008***						
	(0.002)						
ln*EnR**ln*IN*^{2}	0.001***						
	(0.000)						
Control variables	Yes		Yes			Yes	
Province FE	Yes		Yes			Yes	
Year FE	Yes		Yes			Yes	
Observations	496		496			496	
R-squared			0.730			0.721	
F-statistic			603.21			478.53	
AR(1)	0.005						
AR(2)	0.137						
Hansen	0.146						

Note: * p < 0.1, ** p < 0.05, *** p < 0.01; Robust standard errors in parentheses.

Table A1
Abbreviations of variables or terms.

Abbreviation	Variables	Definition
PGDP	Economic growth	Real GDP per capita at constant 2005 prices.
GDP	Gross domestic product	Gross domestic product
EnR	Environmental regulation	Treatment input required per unit of pollutant
y	Industrial pollution investment	Total amount of industrial pollution investment
po	Pollutant discharged	The amount of pollutant discharged of industrial wastewater, industrial sulfur dioxide and industrial smoke (powder)
IN	Green innovation	Quantity of green patents granted
hc	Human capital	Ratio of the number of junior college or above to population aged 6 and over
ur	Urbanization	Ratio of urban permanent population to total population
op	Openness	Proportion of total imports and exports to GDP
gov	Government support	Proportion of fiscal expenditure to GDP
ter	Industry structure	Ratio of the added value of tertiary industry
Abbreviation	Terms	
CNRDS database	Chinese research data services	
FE	Fixed effect	
Conf. Interval	Confidence interval	
LR statistics	Log-likelihood ratio statistics	

so as to reduce pollution treatment cost (Liu, et al., 2018). The new technologies development can not only cut environmental costs, but also improve urban carbon emission efficiency, improve enterprise competitiveness, and promote healthy and efficient economic development. This conclusion lays the foundation for the following analysis on threshold effects.

Table 5 confirms the threshold effect of innovation. In fact, the application of green innovation is also a hidden screening of enterprises (Daniela and Marco, 2022). Some high pollution enterprises with difficulty in bearing the cost of green innovation are gradually eliminated or transformed in market competition. The surviving enterprises have high green innovation capabilities and willingness to innovate. When facing the pressure of environmental regulation, enterprises prefer to respond to environmental protection policies by means of green innovation (Zhang et al., 2019). Meanwhile, enterprises also have the corresponding technological foundation to reduce pollution treatment costs and improve productivity through green innovation. At this stage, economic development is of high quality. When green innovation quantity is higher than the threshold value, the influence of green innovation on economic growth increases, thereby reducing the environmental regulation's marginal effect on economic growth, which means that green innovation reduces the enterprises' pressure to cope with governance costs. When green innovation capabilities are strong, there is not need to rely entirely on excessive environmental regulations to stimulate economic growth. There are many important factors that lead to a non-linear relationship between environmental regulation and economic growth, such as directed technological change (Tang et al., 2019); Digital economy (Wang and Zhang, 2022); Health human capital (Song et al., 2021), etc. My research also adds an important factor - green innovation.

The heterogeneity analysis results in Table 6 indicate that there are region differences in the threshold effect of green innovation. Due to the existence of regional administrative power, environmental regulations across administrative regions or spaces have different impacts on economic growth (Li et al., 2021b). In the eastern and central regions, environmental regulations can significantly promote economic growth when green innovation fails below the threshold, while above the

Table A2
Correlation test.

	lnPGDP	lnEnR	lnIN	hc	gov	urban	open	ter
lnPGDP	1	0.469***	0.829***	0.829***	−0.097**	0.793***	0.476***	0.543***
lnEnR	0.469***	1	0.438***	0.549***	−0.434***	0.605***	0.378***	0.124***
lnIN	0.829***	0.438***	1	0.617***	−0.337***	0.607***	0.424***	0.262***
hc	0.829***	0.549***	0.617***	1	−0.042	0.833***	0.409***	0.547***
gov	−0.097**	−0.434***	−0.337***	−0.042	1	−0.034***	−0.515***	0.336***
urban	0.793***	0.605***	0.607***	0.833***	−0.034***	1	0.635***	0.444***
open	0.476***	0.378***	0.424***	0.409***	−0.515***	0.635***	1	0.269***
ter	0.543***	0.124***	0.262***	0.547***	0.336***	0.444***	0.269***	1

Note: ***<0.01, **<0.05.

Table A3
Panel unit root test.

variables	LLC	IPS
lnPGDP	−15.523***	−9.652***
lnEnR	−3.865***	−4.684***
lnIN	−6.915***	−3.017**
hc	−2.623**	−6.879***
ur	−9.436***	−3.436***
op	−3.716***	−3.584***
gov	−10.143***	−3.541***
ter	−5.8441***	−2.925**

Note: removing cross-sectional means from data.

Table A4
Panel granger causality test.

Null hypothesis	z-bar stat.	Prob.
lnEnR does not Granger-cause *lnPGDP*	−2.410	0.016
lnPGDP does not Granger-cause *lnEnR*	3.366	0.001
lnIN does not Granger-cause *lnEnR*	3.166	0.902
lnEnR does not Granger-cause *lnIN*	5.226	0.000
lnIN does not Granger-cause *lnPGDP*	11.715	0.000
lnPGDP does not Granger-cause *lnIN*	1.2442	0.336

Table A5
Panel cointegration test.

method		statistic	p-value
Kao	ADF	−3.111	0.001
Pedroni	PP	7.518	0.000
	ADF	−1.610	0.053

Table A6
Bootstrapping analysis.

Mediator	Effect	Observed Coef.	Bootstrap Std. Err.	P>|z|	[95% Conf. Interval]
ln*IN*	Indirect effect	−0.049	0.006	0.000	(-0.062, −0.037)
	Direct effect	−0.019	0.006	0.003	(-0.031, −0.006)

threshold, although still promoting, the impact will decline. Similar to the conclusions of Fan and Sun (2020), we all believe that the Potter effect is applicable in some regions. Moreover, I have found that the Potter effect in the eastern and central regions decreases with the growth of green innovation capabilities. One of enterprises' goal is to maximize profits. When the government releases a signal to control environmental pollution, enterprises respond quickly and are able to sensitively convert production methods and quickly transform to clean enterprises. The high-tech enterprises in the central and eastern regions are relatively dense, they have a wealth of technical talents. In the long run, there will not be a situation where the level of green innovation is insufficient, leading to increased costs and exceeding income. Enterprises face fierce competition, and those unable to withstand environmental regulations will be quickly squeezed out, while clean enterprises will fill the gap immediately. The impact of environmental regulations on economic growth is positive in the central and eastern regions.

In the western region, environmental regulations have a significant inhibitory effect on economic growth when green innovation is at a low threshold. When green innovation is at a high threshold, the inhibitory effect decreases. The possible reasons lie on the backward economic development level or geographical environmental factors, inconvenient transportation, slow development of the secondary industry, and relatively light pollution levels. Strict environmental regulations and green innovation cannot drive economic growth, but may instead inhibit economic growth due to mandatory spending on environmental governance. With the improvement of green innovation in the western region, enterprises have found that green innovation brings about improvements in clean technology and production efficiency, which can more benefit them. Therefore, they strive to transform into clean enterprises, enhance their comprehensive strength, and reduce the effect of environmental regulations in inhibiting economic growth.

There are many heavy industry production bases in Northeast China, and the manufacturing industry is developed. Its economic growth is largely dependent on manufacturing industries. There are many heavily polluting enterprises in Northeast China, and achieving transformation is currently a major challenge. When green innovation is below the threshold, environmental regulations are positive. However, when green innovation achievements cannot bring high profits, coupled with pollution control cost, the overall business performance of enterprises is constrained, which has a negative impact on economic growth.

Generally, the measurement of environmental regulation and green innovation can be quantified from many perspectives, such as environmental regulation is calculated by the percentage or quantity of patents

Table A7
Threshold test and threshold values.

Threshold variable	Threshold effects	F-statistics	p-values	Critical values			Threshold values	95% conf. Interval
				1%	5%	10%		
ln*IN*	single	93.92***	0.000	62.178	37.716	30.770	5.684	(5.611,5.690)
	double	49.08***	0.004	41.976	30.917	24.845	7.964	(7.955, 7.976)
	Triple	34.97	0.748	106.647	93.268	81.215	8.824	(8.733,8.855)

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table A8
Threshold test for each regions.

Regions	Threshold effects	F-statistics	p-values	Critical values 1%	5%	10%	Threshold values	95% conf. Interval
Eastern	single	50.45**	0.045	69.778	49.734	37.793	4.382	(4.138,4.503)
	double	12.39	0.519	55.174	39.707	32.463	7.932	(7.506,7.955)
	Triple	9.67	0.708	79.526	52.715	41.138	8.825	(8.733,8.872)
Central	single	31.10*	0.080	47.769	34.859	29.628	6.553	(6.501,6.603)
	double	9.20	0.633	40.441	30.298	23.724	7.585	(7.536,7.592)
	Triple	6.60	0.753	102.860	64.650	49.438	8.594	(8.530,8.696)
Western	single	28.39*	0.086	45.030	33.054	27.054	3.761	(3.738,3.807)
	double	6.79	0.717	36.399	24.798	20.569	4.635	(4.595, 4.663)
	Triple	4.68	0.736	24.115	24.115	14.261	5.037	(4.950, 5.118)
Northeastern	single	50.73***	0.000	32.520	32.520	20.732	5.347	(5.182,5.389)
	double	−2.97	1.000	40.449	35.619	32.383	5.974	(5.802,6.036)
	Triple	3.82	0.981	38.769	38.769	25.971	6.123	(6.114,6.203)

on environmental technologies (Murshed et al., 2021; Wang et al., 2022), or the weighted value of five indicators (Du et al., 2021). Green innovation is measured by R&D expenditure (Mbanyele 2021). Each measurement method has its own characteristics, it is difficult to quantify it accurately. Referring to the approach of some scholars (Wang and Li, 2015; Zhang et al., 2021; Li et al. 2022), I select Formula (7) to evaluate environmental regulation, and the quantity of green patents granted to evaluate green innovation. When estimating the econometric model (Table 2-Table 7), I try to avoid the impact of regional differences in data quality as much as possible, I introduce both fixed time effects and fixed province effects into models. In order to observe whether there will be significant changes in results due to different indicators, I conducted a robustness test. I use the pollution control amount per unit of sulfur dioxide emissions (*lner1*) as another measure of environmental regulation, and the number of green utility patents granted to represent green innovation. In addition, William and Wang (2022) used a-listed firms from 2008 to 2016 to study environmental regulations and technological innovation, which is a very valuable practice to learn from. I mainly consider the region impact, the data adopts panel data combined by cross-section and time. If there is panel data on the environmental governance costs and green innovation quantity of industrial enterprises, it will undoubtedly be of greater help to this study. In future research, I should have a further study of the construction of green innovation and environmental regulation indicator systems.

Although in heterogeneity analysis, I have provided some discussion from various regions' economic development, transportation environment, and others, in fact, green innovation is closely related to many factors, such as the infrastructure of green innovation (Razzaq et al., 2021; Song et al., 2023), knowledge spillovers (Ester and Rasi, 2019; Wissal et al., 2018), and some possible one-way or two-way impact relationships, they may have spillover effects on the relationship between economic growth and environmental regulation.The factors considered in this artical maybe relatively simple, which is one of limitations. In future research, I will incorporate more influencing factors into the study framework.

7. Conclusions and implications

This study discusses and explores the role of green innovation in the impact of environmental regulation on economic growth. Based on China's provincial panel data from 2005 to 2020, I employ the stepwise regression model to analyze the mechanisms of environmental regulation driving economic growth, and employ the panel threshold regression model to analyze the threshold effect of green innovation.

The findings confirm that environmental regulation drive economic growth effectively. Mechanisms analysis presents that they are influenced by the intermediary role of green innovation, the specific performance is as follows: Environmental regulation can actively stimulate enterprises' green innovation and can boost economic growth by forcing enterprises to execute green innovation. At the current period of high-quality development of China's economy, environmental regulation has an "innovative compensation" effect at the regional level as a whole, which accords with the Porter hypothesis.

In addition, the nonlinear impact of environmental regulation on economic growth is contingent on the threshold effect of green innovation, with diminishing marginal effects. There are two green innovation thresholds. When it is both below the first threshold and between two, environmental regulation has a positive effect on economic growth. But, once the second threshold is exceeded, environmental regulations have a negative impact on economic growth. Of course, I don't think the threshold for green innovation is high, it's below the national average.

I try to examine the mechanism of the three from different regions. Heterogeneity analysis results show that the green innovation threshold in the central region is higher than the mean value of the whole nation, while the threshold in the eastern China is the lowest. The marginal effect of the central and eastern regions decreases, but both are positive. With the increasing numbers of green innovations, environmental regulation still stimulates economic growth, but velocity of increase slows down. In the western and northeastern regions, when the green innovation threshold reaches 5.037 and 5.347 respectively, environmental regulation may inhibit economic growth. This study reflects that green innovation cannot be ignored in the process of environmental regulation promoting economic development.

According to the research conclusion, the following suggestions are put forward. Firstly, the government should constantly improve environmental regulatory policies during the process of promoting high-quality economic development. Governments can take a variety of ways to regulate the environment, not a single mandatory approach. For example, tax incentives or subsidies can be provided to clean companies to stimulate innovative activities. For polluting enterprises, the government can provide them with opportunities for exchanges and cooperation with foreign clean enterprises, so as to promote the transformation and upgrading of industry. Secondly, strengthening innovation-driven development of industry and bringing into play "innovation compensation" effect of environmental regulation. The government ought to continuously adjust and improve the innovation-driven mechanism to promote industrial upgrading and transformation. Managers should increase support and financial subsidies for green innovation, give appropriate policy support to green innovation enterprises, and encourage enterprises to carry out innovative activities. Thirdly, establishing an appropriate environmental access mechanism to prevent highly polluting enterprises from easily getting into the central and western China. With the introduction of the strategy of "energizing the central region", "revitalizing the northeast" and "advancing development in the western region", it is inevitable to undertake the transfer of many high-polluting and high-emission enterprises in the process of industrial transfer. Local governments should set up appropriate environmental access mechanisms to stop the western and central China from becoming "pollution refuges" in the eastern region, strictly abide by the bottom line of the environmental protection regulations, reduce the pollution risk problems caused by the introduction of polluting enterprises. Finally, we should attend to the appropriate number of green innovations. Green innovations do not always make a contribution to environmental regulation and economic growth, higher green innovation will bring pressure and burden to enterprises, thereby limiting the rise effect of environmental regulation to economic growth. Excessive pursuits of green innovations for the sake of environmental regulations can inhibit economic growth. Therefore, managers need to control the number of green innovations.

CRediT authorship contribution statement

Fang Wang: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Funding acquisition.

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.

Data availability

Data will be made available on request.

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Appendix A

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Further reading

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