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Research on the impacts of dual environmental regulation on regional carbon emissions under the goal of carbon neutrality-the intermediary role of green technology innovation

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As an important means to promote regional low-carbon development, environmental regulation has great theoretical and practical significance for achieving the goal of carbon-neutral development in China. Based on the panel data of 30 provinces and cities in China from 2005 to 2019, this paper first uses the intermediary effect model to analyze the impact of the implementation of environmental regulation policies on regional carbon emissions, discusses the relationship between environmental regulation, green technology innovation and carbon emissions, and further uses the threshold effect model to discuss the nonlinear relationship between environmental regulation and regional carbon emissions. The results show that: the improvement of formal and informal environmental regulation can play a role in "forced emission reduction"; Green technology innovation plays a complete intermediary role in the impact of environmental regulation on regional carbon emissions; At the same time, the impact of formal and informal environmental regulation on regional carbon emissions has a threshold effect. Among them, formal environmental regulation has a double threshold effect, the threshold values are 0.429 and 0.502 respectively, while informal environmental regulation has a single threshold effect, the threshold value is 1.803. The results of heterogeneity analysis show that there are obvious differences in the implementation effects of environmental regulation policies under different economic development levels and industrialization development stages. Therefore, we should pay attention to the mutual promotion effect of different types of environmental regulation, strengthen the collaborative emission reduction of environmental regulation and green technology innovation, and improve the level of regional green technology innovation, so as to better promote the realization of regional carbon neutrality goals.

KEYWORDS

carbon neutralization target, environmental regulation, green technology innovation, intermediary effect, carbon emissions, threshold effect

1 Introduction

The conflict between economic growth and environmental conservation has grown more severe as a result of China's resource-dependent rapid economic development during the last 40 years, which has also resulted in massive use of natural resources (Yu et al., 2016; Bai et al., 2021; Zhang et al., 2022). Because of the impact of reckless development to the world's climate challenges, China has proposed that peak CO_2 emissions occur around 2030 and that carbon neutrality be achieved by 2060. The country's carbon neutrality objective reflects China's desire to address climate change and the importance it placed on low-carbon development (Khan et al., 2021; Z.-Z. Li et al., 2021; Xu et al., 2021; Zhou et al., 2022). Since the Kyoto Protocol's passage, China has progressively assumed worldwide responsibility for reducing emissions (Cheng et al., 2022; G. Liu & Zhang, 2022; Qin et al., 2019). The Paris Agreement has defined China's crucial position in the international arena, and environmental regulatory policies have begun to play a larger role.

To achieve the development goals of "carbon peaking" and "carbon neutrality", it is important to highlight the importance of promoting "green development" to promote high-quality regional economic development (A. Wang et al., 2021). Thus, the Chinese government has implemented various environmental regulation policies to improve regional environmental governance and give full play to the role of green technology innovation in reducing emissions (X. Liu et al., 2022; Pan et al., 2017). The implementation of policies and measures related to environmental regulation can reduce the damage to the environment by limiting the production capacity of high pollution and high emission enterprises (Shi et al., 2021; Yirong, 2022). At the same time, it can also improve the level of green technology innovation of enterprises by optimizing the energy structure and increasing R&D investment, so as to achieve emission reduction (W. Cai & Ye, 2020; Xie et al., 2022). In addition, improving the level of green technology innovation plays an important role in giving better play to the emission reduction effect brought about by the implementation of environmental regulation policies (Gu et al., 2022).

When supporting high-quality economic growth, the role of environmental policy in fostering regional green and low-carbon development should be considered. There are two schools of thinking on how environmental regulation affects regional carbon development: the "cost compliance theory" and the "Porter hypothesis" (H. Wu et al., 2020). On the one hand, environmental legislation raises the cost of local environmental management, squeezing out resources for production and R&D, and has a negative impact on the low-carbon expansion of relevant enterprises (Fernando and Wah, 2017; Martín-de Castro et al., 2017). Strong environmental restrictions, on the other hand, may encourage corporations to accelerate innovation and R&D, thereby supporting the development of green technologies (Hu et al., 2020). Environmental regulation can assist firms in incorporating environmental considerations into production decisions and successfully directing corporate technological innovation (Khalfaoui et al., 2022; Khanh Chi, 2022). This will result in a win-win situation for regional economic growth and reduced CO_2 emissions. In this context, clarifying the internal linkages between environmental regulation, green technological innovation, and local carbon emissions might benefit in the investigation of more rational forms of environmental regulation and the formulation of more scholarly ecological preservation plans.

In comparison to earlier studies, this paper's potential contributions to existing research include the following: First, it examines the impact of official and informal environmental legislation on regional carbon emissions in the context of achieving carbon neutrality goals. Second, it discusses green technology innovation's mediating role and analyzes the critical significance of green technology innovation in regional carbon emissions under the effect of environmental legislation. Third, a threshold regression model is incorporated to investigate the impact of formal and informal contexts on thresholds. Fourth, the impact of various forms of environmental legislation on regional carbon emissions is explored in terms of both regional economic development level and heterogeneity of industrialisation development stages.

2 Literature review

Carbon dioxide emissions reduction is an urgent issue, and research on carbon emissions has focused on calculating and estimating various types of carbon emissions, their regional characteristics and influencing factors (T.-H. Wu et al., 2018), their effectiveness (B. Cai et al., 2018), and prospective future carbon reduction pathways (S. Wang et al., 2016). Environmental regulation is recognized as a useful instrument for decreasing environmental difficulties among them. Environmental regulation primarily refers to governments developing proper public policies and processes to control and limit the economic and production practices of relevant enterprises (Fowlie et al., 2012). Public goods and adverse externalities are also distinguishing features of environmental control. The present environmental regulatory tools are classified as formal and informal, with both having a substantial impact on the environmental performance of company operations (Clò et al., 2017).

The researchers are now focusing their study on how environmental laws affect local carbon emissions on the

following topics (Sinn, 2008; Quentin Grafton et al., 2012; Werf and Maria, 2012). The first researcher to propose a "green paradox" argued that implementing environmental control policies would increase fossil fuel consumption and summarized three major reasons for the "green paradox," namely incorrectly set carbon taxes, policy instruments to reduce fossil fuel demand, and lagging policy implementation (Brunnermeier & Cohen, 2003; Smulders et al., 2012; Reynaert, 2014). Second, environmental legislation has the potential to "force emission reductions." The reversal force of environmental legislation encourages businesses to engage in technological innovation and deploy resources more prudently (Porter & van der Linde, 1995; Popp, 2006). Strengthening environmental regulation can realize the transfer of local high-emission industries and promote the reduction of carbon emissions in the region (Yin et al., 2015). Third, environmental regulation and carbon emissions have a non-linear relationship (Wenbo & Yan, 2018). Environmental regulation converts external pressure into incentives for enterprises to innovate by imposing external pressure on firms to overcome inertia (Ambec & Barla, 2002; Fischer et al., 2003). The scope, cost, and marginal environmental benefits of innovation all have an impact on environmental regulatory quality.

According to the research findings, earlier studies frequently focused on the relationship between environmental regulation and carbon emissions, with few studies analyzing the relationship between the three from the standpoint of green technology innovation. There were numerous studies that looked at the relationship between technological innovation and carbon emissions. An in-depth study on the function of environmental regulation in supporting regional carbon emission reductions, on the other hand, has substantial theoretical and practical implications for the implementation of low-carbon regional economic development. Therefore, from the standpoint of green technology innovation, this article examines the impact and mechanism of formal and informal environmental regulation on regional carbon emissions in order to propose some ideas and references for better fostering the regional economy's low-carbon development.

3 Theoretical analysis and research hypotheses

To optimize the impact of regional carbon emission reductions, carbon emissions produced during production and daily living must be reduced (Z. Li et al., 2020; Q. Wu, 2022). This is one of the objectives of both formal and informal environmental regulations. However, the various implementation concerns and regulatory strategies have very varied implications for carbon emission reduction (Ke et al., 2022). Formal environmental regulation, which emphasizes mandatory restriction through laws, systems, and other ways, has an impact on the entire industrial process (Chen et al., 2022; Cui et al., 2022). The fundamental goals of informal environmental control are to use soft limitations to monitor, manage, and penalize pollution discharge. Therefore, Regional carbon emissions have historically been suppressed more by government-led formal environmental regulation than by informal environmental regulation (Arimura et al., 2019). Furthermore, due to the impact of policy execution, formal environmental management has the features of long-term sustainability in terms of temporal and spatial variation (Kong et al., 2021; Muratoglu et al., 2022). The public's natural interest for environmental protection is the primary focus of informal environmental control. Changes in environmental quality are more likely to affect efforts taken consciously to improve one's living environment (Genc & De Giovanni, 2021). Furthermore, the effects of various types of environmental regulation on the reduction of carbon emissions vary by location due to disparities in regional economic development levels and resource endowments. As a result, the following principles are established:

Hypothesis 1: improving the intensity of environmental regulation can promote the level of regional carbon emission reduction, and there are differences between the role of formal and informal environmental regulation.

In order to achieve low-carbon development in the area, it is critical to enhance source control in addition to environmental legislation. It is possible to ensure that regional carbon emissions are consistently reduced by mandating firms to improve production and emission technology (Cong et al., 2020; Clora & Yu, 2022; Geroe, 2022; Yang & Lee, 2022). Thus, increasing the level of green technology innovation within businesses can not only hasten the transformation of high-carbon businesses and improve their core competitiveness, but it can also benefit from the synergistic emission reduction effect of environmental regulation and stimulate regional emission reduction potential (Sovacool et al., 2019; Pulicherla et al., 2022). Increasing R&D spending can pave the way for a new development path for local carbon emissions by increasing the region's level of innovation in green technologies. Therefore, this paper proposes the following assumptions:

Hypothesis 2: in the process of promoting regional carbon emission reduction by environmental regulation, green technology innovation plays an intermediary role.

Adoption and execution of environmental control legislation can help reduce regional carbon emissions by increasing enterprises' capacity to develop green technologies (Lukman et al., 2018; Ribeiro et al., 2018; Al Baroudi et al., 2021). It is probable that this method of promotion is linear. Formal environmental regulation cannot totally prevent the change in carbon emissions and carbon intensity during the early phases of adoption due to the consequences of rapid economic expansion (Hensher, 2020). The relationship between informal environmental regulation and the growth in living quality, which has an impact on the quality of the ecological environment, causes a decline in the impact of non-environmental regulation's ability to reduce carbon emissions (Ge et al., 2020; Dogan et al., 2022; Xia et al., 2022). Hence, only when environmental regulation reaches

a particular level will it be able to better stimulate the potential for regional carbon emission reduction and contribute to regional green development. Based on the preceding study, the following assumptions are advanced in this paper:

Hypothesis 3. the impact of environmental regulation on regional carbon emissions may have a nonlinear threshold effect.

4 Research design

4.1 Model specification

4.1.1 Mediating effect model

This paper focuses on the links between official and informal environmental legislation, green technology innovation, and carbon emissions. However, it is still necessary to investigate how diverse environmental legislation affect local carbon emissions through green technologies. As a result, environmental control is divided into formal and informal categories, which serve as the primary explanatory elements. As control variables, the benchmark measurement model includes the six indicators of GDP per capita, urbanisation rate, industrial structure upgrading, energy consumption level, government expenditure, and foreign capital dependency. The intermediary variable is green technology innovation. The exact model settings are as follows:

$$lnCar_{i,t} = \alpha_0 + \alpha_1 lnCar_{i,t-1} + \alpha_2 ER_{i,t-1} + \alpha_3 FER_{i,t-1} + \sum_{k=1}^{6} \alpha_2 control_{i,t-1} + \omega_i + \nu_t + \varepsilon_{it} \quad (1)$$

In addition, in order to further test the relevant hypotheses put forward above, the intermediary effect of green technology innovation is analyzed, and the following three dynamic panel regression models are established:

$$lnCar_{i,t} = \beta_0 + \beta_1 lnCar_{i,t-1} + \beta_2 ER_{i,t-1} + \beta_3 FER_{i,t-1} + \sum_{k=1}^{6} \beta_4 control_{i,t-1} + \omega_i + \nu_t + \varepsilon_{it} \quad (2)$$

$$lnCar_{i,t} = \theta_0 + \theta_1 lnCar_{i,t-1} + \theta_2 ER_{i,t-1} + \theta_3 FER_{i,t-1} + \sum_{k=1}^{6} \theta_4 control_{i,t-1} + \omega_i + \nu_t + \varepsilon_{it} \quad (3)$$

$$lnCar_{i,t} = \gamma_0 + \gamma_1 lnCar_{i,t-1} + \gamma_2 ER_{i,t-1} + \gamma_3 FER_{i,t-1} + \gamma_4 lnGTI_{i,t-1} + \sum_{k=1}^{6} \gamma_5 control_{i,t-1} + \omega_i + \nu_t + \varepsilon_{it} \quad (4)$$

Where i represents provinces, t represents time, Car represents regional carbon emissions, GTI represents green technology innovation, ER refers to the formal environmental regulation level, FER refers to the informal environmental regulation level, $control$ refers to the control variable, and the control variable is treated with a lag period to reduce the endogenous interference to the model. ω, ν and ε represent individuals, time and random effects respectively. Models (2), (3) and (4) represent the three steps of mediating effect test. Model (2) is used to test the regression impact of environmental regulation on carbon emission change, If the coefficients β_2 and β_3 are significantly positive, the mediating effect test continues. Model (3) is used to test the regression impact of environmental regulation on green technology innovation and analyze the significance level of the coefficients θ_2 and θ_3. Model (4) is used to test the joint impact of environmental regulation and green technology innovation on regional carbon emissions. If the coefficients γ_2、γ_3 and γ_4 are significant and the coefficients θ_2 and θ_3 are not significant, it indicates that green technology innovation has a complete intermediary effect between environmental regulation and carbon emission reduction; if θ two and θ If the coefficients θ_2 and θ_3 are significant, it indicates that green technology innovation plays a part of the intermediary role. Otherwise, the existence of the intermediary role needs to be verified by the Sobel test.

4.1.2 Threshold regression model

Considering the differences in economic development level and resource endowments in different regions, there is also obvious heterogeneity in the effect and potential of regional carbon emission reduction. The technology spillover from the implementation of environmental regulations also has a certain impact on regional carbon emission reduction. So, what are the differences in the impacts of green technology innovation on carbon emissions in different regions? Does the promotion of environmental regulation to the realization of regional carbon emission reduction targets depend on green technology innovation? This paper adopts the Hansen threshold model (Hansen 1999) to deeply describe this nonlinear effect. The construction form of the single threshold model is as follows:

$$Y_{it} = \beta_i x_i + \varepsilon_i q_i \le \gamma \quad (5)$$

$$Y_{it} = \beta_i x_i + \varepsilon_i q_i > \gamma \quad (6)$$

Where β Is the regression parameter, q is the threshold variable, and r is the threshold value. When there are two or more thresholds, the model structure needs to be further extended. Therefore, this paper adopts the double threshold model for analysis, with environmental regulation as the threshold variable. The specific model form is as follows:

$$\ln\ Car_{i,t} = \mu i + \beta_1 I(ln\ ER_{it} \le \gamma_1) + \beta_2 I(\gamma_1 < ln\ ER_{it} \le \gamma_2) + \beta_3 I(ln\ ER_{it} \gamma_3) + \beta_4\ ln\ FER_{it} + \beta n \sum_{k=1}^{6} control_{i,t,k} + \epsilon_{it} \quad (7)$$

$$ln\ Car_{i,t} = \mu i + \beta_1 I(ln\ FER_{it} \le \gamma_1) + \beta_2 I(\gamma_1 < ln\ FER_{it} \le \gamma_2) + \beta_3 I(ln\ FER_{it} \gamma_3) + \beta_4\ ln\ ER_{it} + \beta n \sum_{k=1}^{6} control_{i,t,k} + \epsilon_{it} \quad (8)$$

Where i and t represent the region and time, u_i represents the characteristic value of the observed value, I (.) is the indicative function, ε_{it}iidN $(0,\delta^2)$ is the random error term, and other variables have the same meaning as above.

TABLE 1 Selection and measuring methods of variables.

Variable		Symbol	Calculation method
Explained variable	Carbon emissions	Car	Energy consumption * Carbon emission factor (100 million tons) (Mynko et al., 2022)
Core explanatory variables	Formal environmental regulation	ER	Ratio of investment in industrial pollution treatment to GDP (Guo et al., 2022)
	Informal environmental regulation	FER	Composite index based on per capita income, population density and human capital (Hao and Peng, 2017)
Mediator	Green technology innovation	GTI	Number of green invention patents and utility model patents authorized by 1000 people (Lu et al., 2022)
	GDP per capita	agdp	GDP/Resident population at the end of the year10000 yuan per person
	Urbanization rate	ur	Urban population/Resident population at the end of the year (Ding et al., 2022)
	Industrial structure		
Control variable	upgrading	ins	Third industry/Second industry
	Energy consumption	ec	Coal consumption/Total energy consumption
	level		
	government expenditure	gov	Proportion of general public budget expenditure of local governments in regional GDP (Pan et al., 2020)
	foreign capital	fdi	Proportion of actually utilized foreign direct investment in regional GDP (Pan et al., 2020)
	dependence		

TABLE 2 Benchmark regression analysis results.

Variable	1	2	3
	lnCar	lnGTI	lnCar
lnGTI			−0.163***
			(−3.24)
lnER	−0.023**	0.061**	−0.081***
	−(2.19)	(2.32)	(−2.65)
lnFER	−0.350)**	0.418)*	−0.372)*
	(−2.23)	(1.86)	(−1.94)
lnagdp	−0.173**	0.209***	0.059**
	(−2.18)	(3.75)	(2.10)
lnur	0.170*	−0.216**	0.342*
	(1.85)	−2.23	(1.76)
lnins	−0.024**	0.062**	−0.036**
	(−2.07)	(2.14	(−2.35)
lnec	0.070*	−0.269***	0.169***
	(1.79)	(−3.65)	(4.06)
lngov	−0.169	0.214**	−0.193**
	(−1.20)	(2.28)	(−2.16)
lnfdi	0.029*	0.034**	0.026**
	(1.75)	(2.35)	(2.19)
Constant	2.019***	1.229**	4.742***
	(4.60	(2.27)	(3.58)
N	450	450	450
R^2	0.862	0.715	0.801

*, **, * * * respectively represent the significant level of 10, 5, and 1%, and the values in brackets are t values.

Table 1 shows the description of variables, mainly including the selection and measurement methods of variables. Make preparations for the following empirical analysis. Explained variable: (1) Carbon emissions (Car): Energy consumption * Carbon emission factor (100 million tons) (Mynko et al., 2022). The increase of greenhouse gases such as carbon dioxide, comes more from the combustion of fossil energy in addition to the natural production. Core explanatory variables: (1) Formal environmental regulation (ER): Ratio of investment in industrial pollution treatment to GDP (Guo et al., 2022); (2) Informal environmental regulation (FER): Informal environmental regulation mainly refers to the restriction of the media, public participation and public opinion on environmental governance. Composite index based on per capita income, population density and human capital (Hao and Peng, 2017). Intermediate variables: (1) Green technology innovation (GTI): Number of green invention patents and utility model patents authorized by 1000 people (Lu et al.,2022). Green technology innovation is mainly through increasing the R & D investment of enterprises and improving the production level of green technology to achieve the goal of low-carbon development of the regional economy; (2) GDP per capital(agdp): The ratio of the total regional GDP to the resident population at the end of the year; (3) Urbanization rate(ur): Urban population/Resident population at the end of the year (Ding et al., 2022). Control variables: In order to reduce the bias of omitted explanatory variables on the regression estimation results and to make the model more representative, the following control variables are included in the model:(1) Industrial structure upgrading(ins): The ratio of the third industry to the second industry in the

TABLE 3 Robust test results.

Variable	lnCar	lnGTI	lnCar
lnGTI			−0.082***
			(−3.12)
lnER	−0.103**	0.056**	−0.089***
	(−2.01)	(2.23)	(−3.82)
lnFER	−0.270**	0.049*	−0.701**
	(−2.16)	(2.04)	(−2.15)
lnagdp	−0.037**	0.138***	−0.454**
	(−2.37)	(3.35)	(−2.07)
lnur	0.185*	−0.129**	0.605*
	(1.71)	(−2.30)	(1.84)
lnins	−0.324***	0.248**	−0.156**
	(−3.60)	(2.33)	(−2.08)
lnec	0.039*	−0.142**	0.076**
	(1.82)	(−2.10)	(2.12)
lngov	−0.047	0.059**	−0.247**
	(−1.32	(2.06)	(−2.24)
lnfdi	0.047*	0.087**	0.240**
	(1.90)	(2.04)	(2.13)
Con_	1.724**	0.486**	3.162***
	(2.48)	(2.35)	(3.29)
N	450	450	450
R^2	0.840	0.726	0.879

*, **, * * * respectively represent the significant level of 10, 5 and 1%, and the values in brackets are t values.

region is used to measure; (2) Energy consumption level(ec): the proportion of coal consumption in total energy consumption; (3) Government expenditure(gov):the proportion of the general public budget expenditure of local governments in the regional GDP. Proportion of general public budget expenditure of local governments in regional GDP (Pan et al., 2020); (4) Foreign capital dependence(fdi): the proportion of local foreign direct investment in the regional GDP. Proportion of actually utilized foreign direct investment in regional GDP (Pan et al., 2020).

4.2 Variable selection and description

4.2.1 Explained variable

1) Carbon emissions (Car). The increase of greenhouse gases such as carbon dioxide, comes more from the combustion of fossil energy in addition to the natural production. Therefore, this paper selects eight kinds of energy consumption such as coal, coke, crude oil and gasoline, and determines the carbon emission coefficients of corresponding varieties by consulting the data to calculate the carbon emissions. The calculation formula of carbon emissions is:

$$Car_{i,t} = \sum_{j=1}^{8} En_{ijt} \times \theta_j \tag{9}$$

Where Car_{it} represents the carbon emission of the ith province, En_{ijt} represents the physical quantity of the jth kind of energy consumption of the ith province in the t year, θ_j represents the carbon emission coefficient of the jth energy.

4.2.2 Core explanatory variables

1) Formal environmental regulation (ER). Environmental regulation refers to the environmental behavior norms and standards formulated by the government, which are mainly used to solve the external diseconomies of the environment. It is a relatively effective means to correct the system failure and the most discussed factor in the carbon emission research. As for the measurement of environmental regulation, academic circles have not formed a consistent standard. Based on the availability of data, this paper uses the ratio of investment in industrial pollution treatment to GDP to measure the value of formal environmental regulation. The specific calculation formula is as follows:

$$ER_{it} = \frac{POL_{it}}{GDP_{it}} \tag{10}$$

Where ER_{it} represents the intensity of formal environmental regulation in the t year of ith Province, POL_{it} represents the investment in industrial pollution treatment in the t year of ith province, and GDP_{it} represents the regional GDP in the t year of ith province.

2) Informal environmental regulation (FER). Informal environmental regulation mainly refers to the restriction of the media, public participation and public opinion on environmental governance. Considering that the improvement of public awareness of environmental protection can effectively promote the level of regional environmental governance, this paper uses the previous methods for reference (Zhao and Sun 2016), and uses the entropy weight method to objectively measure the intensity of informal $_e$nvironmental regulation.
3) Green technology innovation (GTI). Green technology innovation is mainly through increasing the R and D investment of enterprises and improving the production level of green technology to achieve the goal of low-carbon development of the regional economy. Therefore, this paper uses the environmental technology field corresponding to the international patent classification as the selection standard, and selects the total number of regional green invention patents and utility model patents to measure the level of green technology innovation.

4.2.3 Control variable

1) GDP per capita. It is measured by the ratio of the total regional GDP to the resident population at the end of the year

TABLE 4 Regression results of the impact of different levels of economic development.

Variable	Eastern		Central		Western	
	lnCar	lnCar	lnCar	lnCar	lnCar	lnCar
lnER	−0.158*** (−2.76)	−0.032*** (−3.02)	−0.186** (−2.32)	−0.251** (−2.18)	−0.092* (−1.91)>	−0.214* (−1.88)
lnFER	−0.362** (−2.14)	−0.532** (−2.25)<	−0.201** (−2.06)	−0.124* (−1.89)	−0.083* (−1.86)	−0.159* (−1.75)
lnagdp		−0.038** (−2.36)		−0.024** (−2.25)		−0.106** (−2.04)
lnur		0.196* (1.86)		0.240* (1.80)		0.186 (1.50)
lnins		−0.310*** (−3.52)		−0.249*** (−2.84)		−0.148** (−2.36)
lnec		0.057** (2.28)		0.034* (1.85)		0.025* (1.75)
lngov		−0.083** (−2.05)		−0.056** (−2.20)		−0.081** (−2.33
lnfdi		0.149** (2.35)		0.056** (2.22)		0.241* (1.74)
Individual fixed	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed	Yes	Yes	Yes	Yes	Yes	Yes
Constant	0.274*** (3.27)	2.236*** (4.12)	1.626** (2.24)	3.010** (4.65)	2.128*** (3.15)	1.129*** (2.89)
R^2	0.756	0.731	0.782	0.693	0.680	0.656
N	180	180	135	135	135	135

*, **, * * * respectively represent the significant level of 10, 5 and 1%, and the values in brackets are t values.

2) Urbanization rate. The ratio of the total urban population in the region to the resident population at the end of the year is used to measure
3) Industrial structure upgrading. The ratio of the third industry to the second industry in the region is used to measure
4) Energy consumption level. It is measured by the proportion of coal consumption in total energy consumption
5) Government expenditure. It is measured by the proportion of the general public budget expenditure of local governments in the regional GDP
6) Foreign capital dependence. It is measured by the proportion of local foreign direct investment in the regional GDP.

4.3 Data sources

Considering the availability of the original data, this paper selects the panel data of 30 provinces and cities in China (excluding Tibet, Hong Kong, Macao and Taiwan) from 2005 to 2019. The data comes from the China Statistical Yearbook, China Energy Statistical yearbook, China Environmental Statistical Yearbook, regional yearbooks and the database of Chinese Economic Information Network. The selection and measuring methods of variables are shown in Table 1.

5 Analysis of empirical results

5.1 Benchmark regression results

In order to more accurately test the impact of formal and informal environments on regional carbon emissions, and analyze the intermediary role of green technology innovation, this paper uses the intermediary effect model to test, and the regression results are shown in Table 2.

Based on the regression results in Table 2, Model (1) shows the regression results of formal environmental regulation and informal environmental regulation on regional carbon emissions, and the coefficients of both are significantly negative at the level of 5%, indicating that improving the level of formal and informal environmental regulation helps to play the role of "forcing emission reduction". This may be because, in the short term, although the implementation of formal environmental regulation policies will increase the cost of pollution control for enterprises, it will also force high carbon emission enterprises to

TABLE 5 Regression results of the impact of industrialization development stage.

Variable	Post industrialization		Late industrialization (second half)		Late industrialization (first half)	
	lnCar	lnCar	lnCar	lnCar	lnCar	lnCar
lnER	−0.306***	−0.816***(−2.82)	−1.013**	−0.082***	−0.792*	−0.513**
	(−2.66)		(−2.29)	(−2.78)	(−1.90)	(−1.99)
lnFER	−0.152**	−1.024*** (−3.23)	−0.186** (−2.30)	−0.242** (−2.20)	−0.086* (−1.93)<	−0.215* (−1.89)
	(−2.06)					
lnagdp		−0.085**		−0.203**		0.124*
		(−2.16)		(−2.32)		(1.87)
lnur		0.176*		0.150*		0.206*
		(1.72)		(1.75)		(1.83)
lnins		−0.036**		−0.082**		−0.124*
		(−2.53)		(−2.30)		(−1.70)
lnec		0.042*		0.053**		0.060**
		(1.86)		(2.12)		(2.18)
lngov		−0.152**		−0.045**		−0.126**
		(−2.02)		(−2.17)		(−2.320
lnfdi		0.069*		0.082		0.147**
		(1.66)		(1.25)		(1.99)
Individual fixed	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed	Yes	Yes	Yes	Yes	Yes	Yes
Constant	0.562** (2.45)	1.036*** (2.82)	1.628*** (3.28)	2.126*** (3.10)	0.617*** (4.15)	0.824** (2.37)
R^2	0.642	0.623	0.601	0.592	0.702	0.692
N	135	135	105	105	210	210

*, **, * * * respectively represent the significant level of 10, 5 and 1%, and the values in brackets are t values.

improve their technological innovation level and increase their R and D investment, so as to ensure the green development of products in the production of the whole life cycle. In addition, the government will accelerate the elimination of enterprises with backward production capacity by increasing the support for green technology innovation of enterprises, so as to improve the pollution control capacity of high pollution and high energy consumption industries. Informal environmental regulation emphasizes the role of public awareness of environmental protection in improving the potential of regional carbon emission reduction. With the continuous enhancement of public awareness of low-carbon and environmental protection, more attention will be paid to the requirements for environmental quality in the process of daily life and consumption, which can indirectly affect the change in regional carbon emission level.

According to the estimation results of comprehensive Models 2) and (3), both formal and informal environmental regulation can promote green technology innovation. After adding green technology innovation variables to Model (3), formal environmental regulation still has a significant inhibitory effect on regional carbon emissions. At the same time, the improvement of the green technology innovation level is also conducive to the realization of regional carbon emission reduction targets. This further shows that the improvement of green technology innovation is one of the effective ways for enterprises to achieve emission reduction through environmental regulation. Although the implementation of formal environmental regulations will increase the cost of pollution control for enterprises, in the long run, enterprise technological innovation can promote the upgrading of enterprise industrial structure, optimize production processes, and achieve low-carbon development in the long run. The coefficient of informal environmental regulation is positive, but the significance level is not high. The main reason is that the public does not have a deep understanding that improving green technology innovation can boost regional carbon emission reduction. The public's response to environmental issues may be limited to traditional government constraints and a lack of understanding of improving the level of enterprise technology innovation.

Among the control variables, GDP per capita, urbanization rate, energy consumption level and foreign capital dependence have a positive impact on regional carbon emissions, while the industrial structure upgrading and government expenditure significantly inhibit the increase of regional carbon emissions, which shows the importance of optimizing industrial structure for improving the potential of regional carbon emission reduction.

TABLE 6 Significance test results of threshold variables.

	Model	F	*p*	BS	Threshold estimate	Critical value		
						10%	5%	1%
Formal environmental regulation	Single threshold	14.258	0.005	500	0.429	4.923	9.841	15.120
	Double threshold	15.412	0.032	500	0.502	5.724	10.225	20.105
	Triple threshold	5.428	0.139	500	0.609	8.029	12.272	26.642
Informal environmental regulation	Single threshold	10.425	0.001	500	1.803	3.642	6.045	15.482
	Double threshold	2.169	0.324	500	2.093	5.625	6.827	16.649
	Triple threshold	4.212	0.189	500	3.148	2.217	6.729	15.024

5.2 Robust test

After the benchmark regression analysis, it is necessary to further ensure the accuracy of the empirical results. Therefore, this paper adopts the method of robustness test to analyze, mainly replacing the indicators of the explained variables, and using the average number of years of education in the region to measure the level of informal environmental regulation. The regression results are shown in Table 3. Comparing Table 2 and Table 3, it can be found that the regression results of the model are basically consistent, and the fitting degree of the model results is high. At the same time, the significance and promotion of formal and informal environmental regulation and green technology innovation are basically the same, which shows that the research results are reliable. This further shows that green technology innovation is an important way for the implementation of environmental regulation policies to affect regional carbon emissions. There is a complete intermediary effect between environmental regulation and green technology innovation, and green technology innovation plays a partial intermediary effect in the promotion of regional carbon emission reduction by environmental regulation. The regression results of the robust test are shown in Table 3.

5.3 Heterogeneity analysis

5.3.1 Based on the difference in economic development level

Considering that the difference in economic development level in different regions may affect the regression results, this paper further divides the samples into eastern, central and western regions for regression analysis. The specific estimation results are shown in Table 4.

From the regression results in Table 4, it can be found that there are obvious differences in the impact of formal and informal environmental regulations on carbon emissions in different regions. For the eastern region, with better factor resources and technological innovation, the implementation of environmental regulation policies can more effectively promote the regional low-carbon transformation and development, so as to improve the overall level of carbon emission reduction. Due to the low level of geographical location and attraction to foreign investment, the central and western regions still need to strengthen the implementation effect of environmental regulation policies in the short term to ensure that they can play a greater positive role in promoting the reduction of regional carbon emissions, although they have good resource endowment conditions.

5.3.2 Based on the difference in the industrialization development stage

The effect of environmental regulation policy may also have an important connection with the promotion of industrialization in different regions. Therefore, based on Chenery's industrial phasing theory, this paper divides the research samples into three periods and estimates the regional panel data at different stages of industrialization development. The regression results are shown in Table 5.

From the regression results in Table 5, it can be seen that in the post-industrialization stage, the regression coefficients of formal and informal environmental regulation are significantly negative at the levels of 1 and 5%, which shows that in the region at this stage, due to the relatively strong level of factor resource allocation and technological innovation, the implementation role of environmental regulation is more obvious. In the regions in the late industrialization (second half) and late industrialization (first half), the level of scientific and technological innovation still needs to be improved, and the impact of informal environmental regulation still needs to be strengthened.

5.4 Threshold model regression results

In the process of environmental regulation affecting the regional carbon emission level, there may be a threshold effect. Only when the intensity of regional environmental regulation reaches a certain scale can it promote regional carbon emissions. Therefore, this paper further sets formal

TABLE 7 Estimation results of the threshold model.

Variable	Variable interval	Coefficient	t	*p*
Formal environmental regulation	ECR ≤ 0.429	−0.026	−1.091	0.629
	0.429 < ECR ≤ 0.502	−0.032	−3.016	0.001
	ECR ≥ 0.609	−0.063	−5.128	0.000
Informal environmental regulation	FECR < 1.803	−0.020	−1.237	0.248
	FECR > 1.803	−0.143	−2.283	0.026

environmental regulation and informal environmental regulation as threshold variables, and uses the threshold regression model to study the threshold effect of environmental regulation on regional carbon emissions. As shown in Table 6, the threshold value and threshold number of threshold variables are determined. The results show that the single threshold effect of formal environmental regulation is significant at the level of 1%, the double threshold effect is significant at the level of 5%, and the triple threshold fails to pass the significance test, indicating that the threshold number is two, and the threshold values are 0.429 and 0.502 respectively. The single threshold effect of informal environmental regulation is significant at the level of 1%, but the double threshold effect and the three threshold effect have not passed the significance test, indicating that the number of thresholds is one, and the threshold is only 1.803. Therefore, this paper studies the double threshold model of formal environmental regulation and the single threshold model of informal environmental regulation.

The threshold model regression results in Table 7 show that for formal environmental regulation, when the formal environmental regulation is less than the first threshold value of 0.429, the formal environmental regulation has an inhibitory effect on regional carbon emissions, but it is not significant. When the intensity of formal environmental regulation is between the first threshold of 0.429 and the second threshold of 0.502, it has a significant inhibitory effect on the increase of regional carbon emissions. When the intensity level of formal environmental regulation is greater than the second threshold value of 0.502, its negative impact on carbon emissions increases. The impact of formal environmental regulation on regional carbon emissions will exist in three stages. At the initial stage of the implementation of formal environmental regulation, due to the lag of policy effect and the region's ability to absorb the implementation of the policy, all regions actively adopt environmental protection policies and eliminate backward production capacity. Although the effect of restraining regional carbon emissions is not significant, with the gradual maturity of the implementation of regional environmental regulation policies and the formation of scale effects, It has a strong role in promoting the level of regional carbon emission reduction. Therefore, with the increasing strength of formal environmental regulation, its positive impact is increasing. The possible reasons are as follows: first, the implementation of China's formal environmental regulation is still in the stage of continuous improvement; Second, the impact of formal environmental regulations on regional carbon emissions is gradually rising. When the informal environmental regulation is less than the threshold value of 1.803, its inhibitory effect on regional carbon emissions is not significant. When the informal environment is greater than the threshold value of 1.803, it has a significant inhibitory effect on regional carbon emissions. This shows that with the development of economy and society, people pay more attention to environmental protection, which can form a supervisory role, thus effectively promoting the low-carbon development of the region.

6 Conclusions and policy recommendations

6.1 Research conclusion

Giving full play to the potential of regional carbon emission reduction and promoting low-carbon development in different regions has important theoretical and practical significance for achieving China's carbon neutrality goal. Based on the panel data of 30 provinces and cities in China from 2005 to 2019, this paper first confirms the intermediary role of green technology innovation by using the intermediary effect model, and focuses on the internal relationship among environmental regulation, green technology innovation and regional carbon emissions. At the same time, the threshold effect model is further used to study the threshold effect produced by environmental regulation, and the heterogeneous impact of the difference between economic development level and industrialization development stage is analyzed. The main conclusions are as follows:

First, lowering local carbon emissions is significantly aided by environmental control. The reduction of carbon emissions is specifically positively impacted by formal environmental regulation at the significance level of 1%, whereas informal environmental regulation has no major effect in encouraging regional carbon emission reduction.

Second, formal environmental legislation has a double-threshold impact on local carbon emissions. Regional carbon

emission reduction can be greatly promoted when formal environmental regulation is higher than the threshold value of 0.429; when it is higher than the threshold value of 0.502, the promotion effect is increased. Regional carbon emissions are subject to a single threshold effect from informal environmental regulation. Regional carbon emissions will be reduced when informal environmental regulation is higher than the threshold value of 1.803.

Third, the impact of environmental policy regulation is notably diverse due to variations in economic development levels and industrialization phases. Among them, the impact of environmental regulation is greater for the eastern region and regions in the post-industrialization period, while the central and western regions and regions in the late industrialization period still need to strengthen the impact of environmental regulation policy implementation.

Finally, green technological innovation can act as a bridge to advance and enhance the degree of environmental legislation to support carbon emission reduction.

6.2 Policy recommendations

Based on the above research conclusions, this paper puts forward the following relevant suggestions:

First, utilize the advantages of formal and informal environmental regulation, as appropriate. To maximize the inherent potential of environmental regulation and compel emission reduction, the government should build a long-term regulatory framework that includes both formal environmental regulation and non-environmental control. Formal environmental regulation implements equivalent control mechanisms for large, medium, and small businesses and focuses on reducing the overall volume and severity of pollution. Raising public knowledge of environmental protection and offering a more practical means for the public to monitor the emissions behavior of businesses are crucial at the level of informal environmental control. The effectiveness of environmental regulation on energy conservation and emission reduction can be improved by enhancing the synergy between official and informal environmental control.

Second, the regional low-carbon development target is tightly coupled with the objective of carbon neutral development, strengthening the interplay between environmental legislation and green technical innovation. In order to achieve a win-win development of regional carbon emission reduction and green technological innovation, both formal environmental regulation and informal environmental limitations can raise the level of enterprise technological innovation. In addition, we should boost business investment in R&D and innovation, enhance the rate at which scientific and technical advances are applied, and assure the long-term growth of their potential for green technology innovation.

Third, consideration should be given to the creation of distinct environmental governance policies and the disparities in development between various geographic areas. To ensure the complementary growth of environmental regulation and green technology innovation, differences in resource endowment and economic power of various regions should be taken into consideration. In addition, it is critical to optimize the energy structure and assure the sensible allocation of industrial structure components. To better utilize technology's role in decreasing emissions, investments in research and development of environmental technology as well as the fraction of clean energy use should be enhanced.

Fourth, to internalize the externalities of regional economic development, the eastern region should pursue emissions trading aggressively. The central area, on the other hand, should expand market-based environmental regulatory mechanisms in a planned and methodical manner, modestly increase environmental criteria, strengthen sewage charge collection, and increase investment in environmental subsidies. Environmental rules and carbon emission requirements should be improved to prevent the overconcentration of highly polluting industries in order to promote the integration and synergistic use of various production aspects. This will result in environmental governance between various regions due to diverse environmental governance policies.

Data availability statement

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

Author contributions

XD: Conceptualization, methodology, software, writing—original draft preparation; YZ: validation, formal analysis, investigation, resources, supervision, funding acquisition, supervision; ML: data curation, writing—review and editing; visualization. WX, writing—original draft preparation, data collection; CQ, date collection, resources, analysis. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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