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RESEARCH ARTICLE

Research on the impact of environmental regulation on enterprise technology innovation—an empirical analysis based on Chinese provincial panel data

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Abstract
Under the pressure of environmental degradation and resource depletion, Chinese companies are confronted with the need for transformation and upgrading promoted by technological innovation. However, environmental regulation can help to promote technological innovation. Based on the panel data of China's 30 provincial levels during 2009–2016, firstly, this paper describes the connotation of environmental regulation and measurement intensity of the regulation. Then, the anti-driving effect of environmental regulation on enterprise technology innovation is analyzed. Finally, this paper analyzes the spatial heterogeneity of environmental regulation on enterprise technology innovation. The empirical results are as follows: (1) formal environmental regulation has effectively enhanced technological innovation of enterprises. However, informal environmental regulation generally can positively drive enterprise technology innovation. (2) The impact of environmental regulation on technological innovation of enterprises is spatially heterogeneous. On the one hand, the impact of formal environmental regulation on technological innovation has significant regional differences. The Eastern China generally supports the "Porter hypothesis," while the Middle of China and Western China have the opposite performance. On the other hand, there is a threshold effect between environmental regulation and technological innovation. When the economic development level of the first lagging period is used as the threshold variable, with the gradual improvement of the economic development level, the technological innovation of the enterprise has the effect of first suppressing and promoting, and then verifying the threshold characteristics of environmental regulation on technology innovation.

Keywords Environmental regulation · Technological innovation · Anti-driving effect · Spatial heterogeneity

Introduction

Since the reform and opening up 40 years ago, China has made prominent achievements in industrialization and the economy has maintained a trend of medium and high growth. However, there are also negative externalities in the production process of enterprises, which are mainly manifested as the increasing deterioration of the ecological environment, the excessive consumption of resources, and so on. Columbia University, Yale University, and the World Economic Forum published the 2018 Environmental Performance Index and it demonstrates that China, as an emerging economy, ranks 120th out of 180 countries. This fully reflects that China's rapid economic development has put a lot of pressure on the environment, and to a certain extent, it shows that China's environmental regulation intensity is relatively weak. In addition, the report of the 19th CPC National Congress clearly indicated that building an ecological civilization is important to sustain development of the Chinese nation. On this basis, improving the intensity of environmental regulation has become a necessary way for China to pursue sustainable development. With the gradual improvement of environmental policies and laws, and the growing rise of environmental protection organizations and environmental protection movements, the ways to implement environmental regulation are increasingly diverse. However, strengthening the intensity of

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environmental regulation may result in an increase in the cost of corporate pollution control, which will affect the market competitiveness of enterprises. Technological innovation can not only promote environmental protection, but also enhance the competitiveness of enterprises by improving the production mode and increasing the utilization rate of production factors, thus achieving sustainable economic development. China's "win-win" situation of pursuing sustainable economic development and environmental protection is inseparable from environmental regulation and enterprise technology innovation. Therefore, researching the relationship between China's environmental regulation and technology innovation of enterprises have a great theoretical and practical meaning for improving the overall strength of Chinese enterprises, promoting steady economic growth and formulating of environmental policies.

In recent years, with China's emphasis on environmental issues and the concern of technological innovation of enterprises, the influence of environmental regulation on enterprise technology innovation has been studied by more and more scholars. The views of scholars are inconsistent, mainly forming the following three views:

First, the environmental regulation reduces the productivity of enterprises and weakens their technological innovation capabilities. From a static perspective, the traditional opinion is that strict environmental regulation can reduce environmental pollution and protect the environment, but also lead to the increase of internal production costs, reduce the output of enterprises, decrease the market competitiveness of enterprises, and hinder enterprises the technological innovation of enterprises (Gray and Shadbegian 2003). Ramanathan et al. (2010) utilized the data of 16 industrial sectors in the UK from 2002 to 2006 and then used structural equation modeling to research the relationship among environmental regulation, economic performance, and innovation capability. The study shown that environmental regulation is conducive to enhancing economic performance of the sectors, but in the short turn, investments in pollution control spending are inclined to passively affect innovation in the industrial sector. This is because in the short term, enterprises invest more in controlling pollution than in technological innovation. Acemoglu et al. (2010) described endogenous and oriented technological changes under the environmentally constrained growth model, which leads to the increase in production costs and therefore hinders technological innovation to some extent.

Second, environmental regulation contributes to technological innovation in enterprises. From a dynamic perspective, Porter and Van Der Linde (1995) argued proper and appropriate environmental regulation is not only reducing the net cost of enterprises to meet regulatory requirements, but also fully stimulating the innovation vitality of enterprises, resulting in the effect of "innovation compensation," and thus improving the competitiveness of enterprises in the international market. After proposing the famous "Porter hypothesis," many scholars at home and abroad use panel data to conduct an empirical analysis on this hypothesis. Rubashkina et al. (2015) took relevant data on the manufacturing sector in European countries from 1997 to 2009 as the research object, studied the "strong" and "weak" versions of Porter Hypothesis, and found that when the number of patent applications was used as the substitution variable for innovation output, environmental regulation had a positive influence on the output of innovation activities. Zhao and Sun (2016) used the related data of China's pollution-intensive enterprises in 2007–2012 to study the actual situation of Porter's hypothesis in China. The results indicated environmental regulations make a significantly weaker active effect on enterprise technology innovation, and there is a faintish Porter hypothesis in the central region, while it is not significant in the western region. Chakraborty and Chatterjee (2017) found that compared to other companies that belong to the chemical sector but do not produce dyes, environmental regulations would increase the average innovation output of Indian dye production chemistry companies by 11 to 61%.

Third, the relation between enterprise innovation and environmental regulation is uncertain. Ramanathan et al. (2017) presented environmental regulations include flexible environmental regulation and inflexible environmental regulation. Flexible environmental regulation is beneficial to enterprise innovation by supporting enterprises to develop new processes to satisfy regulatory requirements; inflexible environmental regulation would result in higher administrative expenses and have an adverse effect on firm performance. Song et al. (2018) divided firms' R&D activities into environmental protection R&D and production R&D. Under the premise that other conditions stay unchanged, environmental regulation contributes to environmental protection R&D, but it hinders production R&D. Jiang et al. (2018), on the basis of the empirical analysis of relevant data for China's technology-intensive manufacturing during 2008–2015, found that industrial environmental regulations negatively affect innovation performance, while regional environmental regulations positively influence innovation performance of enterprise. Yuan and Xiang (2018) took the related data of China's manufacturing industries between 2003 and 2014 as the object of study to analyze the impact of environmental regulation on innovation of manufacturing industry. In the short run, the impact of manufacturing R&D investment from environment regulation is inconspicuous. However, environmental regulation adversely impacts R&D investment in the long run.

In addition, some scholars have carried out extensive research on environmental regulation and enterprise technology innovation. For example, Yuan et al. (2017) divided 28 manufacturing industries into three categories according to the level of ecological efficiency. Research indicated the influence of environmental regulations on technology innovation has industry heterogeneity. Among them, for industries with high and low ecological efficiency, the influence of environmental regulation on technological innovation shows an inverted "U" shape. Cao et al. (2017) analyzed the relationship between environmental regulation of 28 manufacturing industries and technological innovation in China from the change rate of three types of environmental regulation intensity: waste water, waste gas, and solid waste. Among them, with the gradual strengthening of environmental regulation intensity of wastewater, its impact on technological innovation presents an "N" type relationship. The influence of waste gas environmental regulation intensity on technological innovation presents an inverted "U" shape. Li et al. (2018) found that when other variables remain unchanged, the implementation of command-and-control environmental regulation is not conducive to the development of environmental technology innovation for the Eastern region, yet it has a positive impact on environmental technology innovation for the Western region. Some scholars believe that there are certain factors that may affect the relationship between environmental regulation and technology innovation, such as the level of social and economic development (Shen and Liu 2012), R&D efficiency (Johnstone et al. 2017), and innovation willingness (De Falco and Renzi 2015), output prices, and knowledge spillovers (Miller 2015).

Through the above literature review, it can be seen that domestic and foreign researchers have made a relatively systematic and comprehensive study about the relationship between environmental regulation and technological innovation. At the present stage, the study for the relationship between environmental regulation and enterprise technology innovation basically presents the following characteristics:

Firstly, most existing studies divide environmental regulations into regional environmental regulations and industrial environmental regulations (Jiang et al. 2018); command-controlled, market-based, and informal environmental regulations (Xie et al. 2017); local regulation and civil regulation (Li and Wu 2017); and economical, supervised, and legal environmental regulations (Liu et al. 2018). Due to the different perspectives of division of environmental regulation, then influence of environmental regulations on technology innovation has not yet reached a unified conclusion. Secondly, some literatures consider environmental regulation as a whole, while others divide environmental regulations from different perspectives. However, when researching the relationship between environmental regulation and technological innovation, few researches consider environmental regulation include formal environmental regulation and informal environmental regulation. Thirdly, nowadays, researches verify the nonlinear characteristics between environmental regulation and technology innovation, and test the threshold effect by introducing threshold variables, while many literatures do not consider the hysteresis when selecting threshold variables.

The remaining part of this paper is structured as follows. The "Connotation and measurement of environmental regulation" section illustrates the connotation of environmental regulation and measurement of regulation intensity. The section "Anti-driving effect of environmental regulation on enterprise technology innovation" provides the empirical model, the main data description, the empirical results, and the robustness tests. In the section "Spatial heterogeneity of environmental regulation and enterprise technology innovation," this paper uses the panel variable coefficient model to examine the differences between formal environmental regulation and technological innovation in different regions; through the threshold regression model, the samples of 30 provinces in China are endogenously grouped to test the threshold characteristics of formal environmental regulation and technological innovation. Conclusions and some policy implications of this paper are given in last section "Conclusions and policy implications."

Connotation and measurement of environmental regulation

Connotation of environmental regulation

With regard to the connotation of environmental regulation, the understanding of the academic community has gone through a process of continuous deepening. Initially, environmental regulation was considered a mandatory regulation and policy set by the government to intervene in the utilization of environmental resources. As environmental issues receive attention and regulatory tools continue to evolve, environmental regulations also include incentive environmental regulations and voluntary environmental regulations. Among them, environmental taxes, pollution control subsidies (Yabar et al. 2013), input and output taxes (Féres and Reynaud 2012), and tradable sewage permits (Costa-Campi et al. 2017) are incentive environmental regulations. Since then, the introduction of informal environmental regulations has further extended the connotation of environmental regulation.

Informal environmental regulation was first proposed by Pargal and Wheeler (1996). When the formal environmental regulation in developing countries is weak or missing, many groups will reach an agreement with local polluting enterprises to reduce pollution emissions for their own interests, which is called "informal environmental regulation." Kathuria (2007) holds that formal environmental regulation in developing countries have certain limitations in pollution control due to information asymmetry in formal environmental regulations in developing countries, thus stressing the importance of informal environmental regulation in achieving environmental goals. Langpap and Shimshack (2010) investigated the lawsuits of ordinary people on environmental pollution incidents and concluded that public sanctions and public supervision, as a means of informal environmental regulation, have played a vital role in the prevention and control of water pollution in the USA. Zhao et al. (2009) believed that environmental regulation is a binding force that protects the environment as a target, a tangible system or an intangible consciousness as the form. Thus, environmental regulation is divided into explicit environmental regulation and implicit environmental regulation. Among them, implicit environmental regulation refers to the inherent, intangible concept of environmental protection, environmental protection thinking, environmental awareness, environmental cognition, etc. Therefore, this paper is the same informal environmental regulation as public awareness of environmental protection.

Measurement of environmental regulation

The measurement of environmental regulation intensity includes formal environmental regulation and informal environmental regulation. According to the connotation of formal environmental regulation mentioned above, this paper summarizes several popular methods for measuring formal environmental regulation intensity: (1) formal environmental regulation intensity is measured by the ratio of pollution control investment to the total output value or cost of industrial enterprises (Lanoie et al. 2008; Jiang et al. 2018); (2) it can be measured by the environmental pressure represented by CO_2 emissions (Marin 2014; Costa-Campi et al. 2017); (3) the operational costs of pollution treatment infrastructures are used to weigh the intensity of formal environmental regulation (Rubashkina et al. 2015); (4) the quantity of local government environmental legislation is adopted as the proxy variable of formal environmental regulation (Acemoglu et al. 2010); (5) the comprehensive index method is used to construct the comprehensive measurement index of formal environmental regulation intensity (Zhao and Sun 2016), which selects indicators such as sulfur dioxide removal rate, waste water discharge rate, and the ratio of solid wastes utilized to examine the emission of various pollutants.

The first four methods have singular defects when selecting indicators. Due to the availability and reliability of the data, indicators such as discharge standard amount and removal amount of industrial waste water in each province after 2011 are no longer counted, so the year studied in this paper is not suitable for adopting the comprehensive index method. Therefore, this paper refers to the method of Shen and Liu (2012) to construct an environmental regulation evaluation index as a proxy variable for the intensity of formal environmental regulation. The method of constructing the indicator has the following steps:

First, the pollution control investment per unit of the industrial output value of each province is calculated as follows:

$$FERI_{it} = \frac{E_{it}}{Y_{it}}$$

where $FERI_{it}^{*}$ indicates the unit industrial output value of province i's investment in pollution control in year t, E_{it} indicates the completed investment in the treatment of province i's industrial pollution in year t, and Y_{it} denotes the total industrial output value of province i in year t.

Second, we need to calculate the annual industrial structure weight of each province. For different provinces, there are differences between industrial structures. In the provinces with heavy polluting industries, the formal environmental regulation intensity will be overestimated. On the contrary, the provinces with clean and environment-friendly industries will have an underestimated formal environmental regulation intensity. The proportion of industrial structure is defined as:

$$FERI_{it} = \frac{Y_{it}}{GDP_{it}}$$

Finally, the industrial structure can be used to modify the intensity of formal environmental regulation to avoid erroneous evaluations. Therefore, the formal environmental regulation intensity is defined as:

$$FERI_{it} = \frac{FERI_{it}^{*}}{FERI} \times 100$$

The greater the value of $FERI_{it}$, the greater the intensity of formal environmental regulation, and vice versa, the weaker the intensity of formal environmental.

Informal environmental regulation is mainly manifested in the public's awareness of environmental protection. Therefore, this paper can weigh the intensity of informal environmental regulation by measuring the environmental awareness of citizens. Compared with formal environmental regulation, informal environmental regulation is less studied. In the existing studies, the informal environmental regulation intensity is mainly measured by the public opinion support rate and literacy rate in parliamentary elections (Goldar and Banerjee 2004), social reputation (Shimshack and Ward 2005), media exposure to pollution events (Kathuria 2007), and other indicators. Besides, Zhao et al. (2009) believe that the level of public environmental awareness may be affected by many factors such as gender, age, education level, income level, and environmental protection efforts. Since most data are difficult to obtain and analyze with quantitative indicators, it is too subjective and inaccurate to use a single indicator to measure informal environmental regulation.

Referring to the method of Pargal and Wheeler, this paper selects the education degree, income level, age structure, and population density to comprehensively measure the informal environmental regulation intensity in each province. The specific indicators are explained as follows: (1) educational level ($IERI_{edu}$): the higher the level of education, the stronger the people's awareness of environmental protection and the higher the public's participation in environmental protection (Wang and Liu 2019). If people are generally highly educated, they will effectively supervise and resist the behavior of manufacturers to pollute the environment, so that the polluting enterprises will transfer to the regions with lower education. In this paper, the proportion of the employed population above junior college level with the education degree in each province is selected as one of the indicators to measure the informal environmental regulation. (2) Income level ($IERI_{wage}$): social groups with higher income levels have higher demands for environmental quality. At the same time, compared with regions with lower income levels, the public in high-income regions pay greater attention to environmental pollution. This paper measures the income level by the average wage level of urban employees. (3) Age structure ($IERI_{age}$): young people pay more attention to environmental issues, have stronger awareness of environmental protection, and are more motivated to participate in non-governmental environmental protection organizations. We use the proportion of the population under the age of 15 to measure the age structure. (4) The population density ($IERI_{den}$): areas with higher population density mean more people are affected by environmental pollution; therefore, more people are involved in environmental activities. The population density is evaluated by the rate of total population to the geographical area. Descriptive statistics of environmental regulation intensity are shown in Table 1.

Anti-driving effect of environmental regulation on enterprise technology innovation

Empirical model

This paper mainly uses panel regression method to research the effect of formal environmental regulation and informal environmental regulation on technology innovation. Formal environmental regulation and informal environmental regulation are included in the model as core explanatory variables, and other influencing factors of technological innovation are also introduced into the model as control variables. In order to avoid heteroscedasticity and multi-collinearity, we perform logarithmic processing on each variable. The econometric model of the influence of environmental regulation intensity on enterprise technology innovation is as follows:

$$\begin{aligned}\ln I_{it} = {} & \beta_0 + \beta_1 \ln FERI_{it} + \beta_2 \ln IERI_{edu,it} + \beta_3 \ln IERI_{wage,it} + \beta_4 \ln IERI_{age,it} + \beta_5 \ln IERI_{den,it} \\ & + \beta_6 \ln FDI_{it} + \beta_7 \ln IL_{it} + \beta_8 \ln IM_{it} + \beta_9 \ln PROFIT_{it} + \varepsilon_{it}\end{aligned} \tag{1}$$

where $i = 1,\ldots, N$ and $t = 2009,\ldots, T$ indicate 30 provinces in China and the year; I_{it} is for technological innovation; FDI_{it} indicates foreign direct investment; IL_{it} indicates labor input in technological innovation; IM_{it} denotes capital input in technological innovation; $PROFIT_{it}$ denotes corporate profit margin; ε_{it} is error term.

Data source, processing, and indicator description

In view of the completeness and availability of the data, this paper adopts the panel data of China's 30 provinces[1] between 2009 and 2016. The data are obtained from the "China Statistical Yearbook," "China Statistical Yearbook on Environmental," "China Statistical Yearbook on Science and Technology," "China City Statistical Yearbook," and local environmental bulletin. This paper refers to all monetary quantity, using the GDP index, consumer price index, and commodity retail price index to reduce to the constant price of the base period in 2009. All variables are annual variables and logarithmic form. The relevant variables are described as follows:

(1) Enterprise technology innovation (I)

At present, scholars measure technological innovation indicators from different perspectives. Enterprise technology innovation usually include two indicators: innovation input and innovation output. The technology innovation ability of enterprises is affected by the level of innovation input to some extent. Among them, the innovation input indicators include internal expenditure of R&D (Cruz-Cázares et al. 2013), full-time equivalent of R&D personnel, and so on. Indicators of innovation output include per capita number of invention patents

[1] The Tibet Autonomous Region, the Macao Special Administrative Region, and the Hong Kong Special Administrative Region are not included in the 30 provinces.

Table 1 The descriptive statistics of core explanatory variables

Variable	Observation	Mean	SD	Min	Max
FERI	240	2.4510	1.607	0.666	7.981
$IERI_{edu}$	240	15.579	9.231	3.240	55.870
$IERI_{wage}$	240	43,355.590	13,271.563	24,696.000	101,378.960
$IERI_{age}$	240	16.360	3.912	7.600	25.200
$IERI_{den}$	240	458.262	680.370	8.000	3825.690

authorized, per capita number of patent applications, number of new product development projects, and new product sales revenues. In China, since the sales scale of new products was difficult to be counted, Jiang et al. (2018) and Mensah et al. (2018) used the number of invention patents per capita to measure the innovation achievements. In addition, Rahko (2016) also believed that inventions can be regarded as a representative of the original innovations. The number of patent applications, number of patent citations, and technical field are used to measure the output, diversity, and quality of innovation. In view of the availability of data, this paper uses the number of patent applications of industrial enterprises above designated size as the proxy variable of technology innovation. The more patent applications, the stronger the technology innovation capability of enterprises.

(2) Foreign direct investment (*FDI*)

Foreign direct investment can be used to measure the degree of a country's openness. With the improvement of China's opening up, on the one hand, the increase of foreign direct investment will have a significant technological spillover effect, thereby improving China's technological innovation capability. In the face of fierce foreign competition, the industry is more motivated to reduce costs, thus stimulating corporate innovation (Kneller and Manderson 2012). On the other hand, it may introduce polluting enterprises while introducing or absorbing large amounts of foreign capital. Companies with higher levels of pollution will choose to establish themselves in countries with loose environmental regulation, which will directly aggravate environmental pollution and make it the "pollution heaven." Ren et al. (2014) argued that the inflow of foreign direct investment would aggravate China's CO_2 emissions, thus supporting the pollution heaven hypothesis. Therefore, this paper selects the actual foreign direct investment amount as an indicator to measure FDI. Using the 2009–2016 annual average exchange rate between China and the USA, the actual foreign direct investment amount was converted into RMB as the currency unit, and the consumer price index based on the 2009 was constructed to offset it.

(3) Technological innovation input (*IL* and *IM*)

Technological innovation inputs include labor input and capital investment. From an input-output perspective, the introduction of talent and R&D investment result in the continuous emergence of innovations (Balsmeier 2017). Rahko (2016) found that increasing R&D investment has a great positive impact on the innovation performance of enterprises and countries. Therefore, this paper uses the number of personnel engaged in R&D activities of industrial enterprises above designated size as the substitution variable of labor input in technological innovation, and the total R&D expenditure of industrial enterprises above designated size as the proxy variable of capital investment in technology innovation. The commodity retail price index is used to reduce the total R&D expenditures of industrial enterprises above designated size.

(4) Corporate profit margin (*PROFIT*)

The corporate profit margin is a comprehensive indicator reflecting the whole of production and operation activities of the enterprise, and is one of the affecting factors of technology innovation of the enterprise. In general, a relatively high profit margin indicates a company has good profitability, and it has a good expectation for its future development and prefers to invest more appropriate funds in technology research and development activities (Jiang et al. 2013). Therefore, this paper introduces the index of corporate profit rate into the model and selects the ratio of the total profit of industrial enterprises above designated size to the net fixed assets as the measure of corporate profit margin.

Empirical tests and results

Before panel regression analysis, the Hausman test results indicate the random effect model is less suitable than the fixed effect model. Therefore, the fixed effect model is used to test the forced effect of environmental regulation intensity on enterprise technology innovation. Regression analysis was performed using Stata15.0, and the results of regression estimation are shown in Table 2. The information in Table 2 indicates that the regression model passes the significance test as a whole, where the F statistic is 238.45 and the accompanying probability is 0.0000, indicating that the measurement model

Table 2 Regression results of panel data

Variables	Coef	*T* statistic	*P* value	SE
c	− 7.6994**	− 2.33	0.021	3.3047
ln*FERI*	0.3011***	6.68	0.000	0.0451
$\ln IERI_{edu}$	0.3348***	3.65	0.000	0.0917
$\ln IERI_{wage}$	0.5044***	2.71	0.007	0.1862
$\ln IERI_{age}$	− 0.5412*	− 1.84	0.067	0.2939
$\ln IERI_{den}$	0.3451	0.50	0.617	0.6898
ln*FDI*	− 0.1137***	− 3.44	0.001	0.0330
ln*IL*	0.4074***	3.38	0.001	0.1205
ln*IM*	0.4842***	3.55	0.000	0.1363
ln*PROFIT*	0.0225	0.66	0.512	0.0342
R^2	0.9144			
F value	238.450 [0.000]			
Hausman chi statistic	32.240 [0.000]			

*, **, and *** show significance at the 10%, 5%, and 1%, respectively. *P* value is in square brackets

setting is reasonable. The influence of each explanatory variable on enterprise technology innovation is analyzed in detail.

Formal environmental regulation promotes technology innovation in enterprises. It can be seen from Table 2 that the intensity of formal environmental regulation is positively related to enterprise technology innovation, and through the significance test, it shows that China's formal environmental regulation has a significant anti-driving effect on enterprise technology innovation. At the 1% level of significance, for every 1% increase in FERI, the number of patent applications will grow by 0.3011%. This is consistent with the previous predictions and supports the Porter hypothesis to a certain extent. With the gradual improvement of China's formal environmental regulation policy, the short-term measures taken by enterprises to cope with environmental regulations are no longer fully effective. Therefore, considering long-term economic benefits, enterprises will increase R&D investment to promote technological innovation.

Informal environmental regulation generally promotes technological innovation in enterprises. The regression results of panel data indicate that education level and income level have a significant good influence on technological innovation of enterprises. For every 1% increase in education level, it will help enterprises to increase their technological innovation activities by 0.3348%; for every 1% increase in income level, technological innovation activities will increase by 0.5044%. Population density has an insignificant positive effect on technological innovation. Only the age structure index has hindered the technological innovation activities of enterprises. In recent years, with the gradual improvement of the income level of the Chinese people and the pursuit of a high-quality living environment, people have gradually maintained their own vital interests through informal environmental regulation, such as more and more exposure of environmental events by the media and increasing public rejection of polluting enterprises.

The influence of other control variables. It can be seen from Table 2 that foreign direct investment has a great hindering effect on technological innovation of Chinese enterprises. For every 1% increase in FDI, corporate innovation activities will be reduced by 0.1137%. This conclusion is consistent with the "pollution haven hypothesis." China vigorously introduces foreign investment, promotes China's economic development, and prompts foreign investors to transfer high-pollution industries and mature technology and equipment to China. This is not conducive to Chinese enterprises' learning and mastering advanced technologies, thus inhibiting China's technological innovation capabilities. R&D expenditure and the number of R&D personnel have a remarkable promoting effect on technological innovation: for every 1% grow in R&D expenditure, the number of patent applications will increase by 0.4074%; for every 1% increase in the number of R&D personnel, the number of patent applications will increase by 0.4842%. It indicates that the technology innovation output of Chinese enterprises relies heavily on technological innovation investment. Corporate profit margin positively and insignificantly affect the number of patent applications, indicating that the higher the corporate profit margin, the more capital investment for technological innovation activities. In the early stage of enterprise R&D, a large amount of capital investment is required for purchasing equipment and hiring innovative talents. Therefore, only companies with sufficient capital and high profitability can engage in technological innovation activities.

Robustness tests

To make the most of the information contained in the panel data and ensure the stability and scientific of the research results, two methods are adopted for the robustness test. The first method is to replace the core explanatory variables. For model (1), the following variables are changed in this paper: ① Per capita GDP is used as a substitute variable for measuring the intensity of formal environmental regulation. Regulation of industrial pollution increases with economic development (Mani and Wheeler 1998). ② The human capital stock, disposable income of urban residents and children dependency ratio in each province are selected to measure the education level, income level, and population structure, respectively, and used as alternative variables to measure the intensity of informal environmental regulation. Among them, the method of Barro and Lee (1993) is used to calculate the human capital stock, and the calculation formula is as follows:

$$HCI_{it} = P_{i1} \times 6 + P_{i2} \times 9 + P_{i3} \times 12 + P_{i4} \times 16$$

where P_{i1}, P_{i2}, P_{i3}, and P_{i4} respectively represent the proportion of the employed population with education degree of primary school, junior high school, senior high school, and junior college and above. The GDP index based on 2009 is used to reduce per capita GDP, and the consumer price index for 2009 is used to reduce the disposable income of urban residents. The Hausman test indicates that the model (1) is suitable for the fixed effect model. As shown in the robustness test in Table 3, the regression results are basically consistent with the previous conclusions.

The second method is to eliminate some samples. Due to the geographical location of China, there are quite differences in the level of opening up and the degree of economic development of various provinces. Therefore, this paper excludes provinces with significant differences in the level of opening up and the degree of economic development. That is to say, the removed samples are Jiangsu, Guangdong, Gansu, and Ningxia provinces, and only 26 samples are retained at last. The specific regression results are shown in Table 4. Except for the age structure indicators in the informal environmental regulation becoming insignificant, the regression coefficients and significance of other variables do not change much, which is consistent with the previous research results. Therefore, the regression results of this paper can be considered to be robust.

Spatial heterogeneity of environmental regulation and enterprise technology innovation

The above content has verified the anti-driving effects of environmental regulation on enterprise technology innovation. However, as for the intensity of formal environmental regulation, does the degree of environmental regulation in China's

Table 3 Method I robust test regression results

Variables	Coef	*T* statistic	*P* value	SE
c	− 27.7570***	− 11.48	0.000	2.4184
ln*FERI*	0.6712**	2.54	0.012	0.2647
ln$IERI_{edu}$	2.1957***	6.96	0.000	0.3153
ln$IERI_{wage}$	0.8390**	2.59	0.010	0.3239
ln$IERI_{age}$	− 0.4016*	− 1.72	0.087	0.2332
ln*FDI*	− 0.0661**	− 2.10	0.037	0.0315
ln*IL*	0.3263***	2.86	0.005	0.1140
ln*IM*	0.3260**	2.55	0.012	0.1279
ln*PROFIT*	0.0448	1.19	0.237	0.0378
R^2	0.9211			
F value	294.930 [0.000]			
Hausman chi statistic	25.940 [0.0011]			

*, **, and *** show significance at the 10%, 5%, and 1%, respectively. *P* value is in square brackets

Table 4 Method II robust test regression results

Variables	Coef	*T* statistic	*P* value	SE
c	− 8.1252**	− 2.42	0.017	3.3604
ln*FERI*	0.3200***	7.00	0.000	0.0457
ln$IERI_{edu}$	0.3078**	3.17	0.002	0.0972
ln$IERI_{wage}$	0.5828***	3.09	0.002	0.1889
ln$IERI_{age}$	− 0.4075	− 1.33	0.185	0.3060
ln$IERI_{den}$	0.3300	0.47	0.641	0.7068
ln*FDI*	− 0.1215***	− 3.49	0.001	0.0349
ln*IL*	0.4373***	3.48	0.001	0.1255
ln*IM*	0.4164***	3.01	0.003	0.1384
ln*PROFIT*	0.0484	1.26	0.209	0.0383
R^2	0.9150			
F value	206.910 [0.000]			
Hausman chi statistic	24.560 [0.0063]			

*, **, and *** show significance at the 10%, 5%, and 1%, respectively. *P* value is in square brackets

provinces have different effects on technological innovation? Does the government need to develop different environmental regulations? According to Porter's research, the conclusion that formal environmental regulation promotes technological innovation should be based on appropriate and reasonable regulatory intensity. Therefore, this paper firstly examines 30 provinces in Eastern China, Middle of China, and Western China, and uses panel variable coefficient models to analyze whether formal environmental regulation intensity has regional differences in technological innovation activities. After that, the threshold panel regression model is used to further research whether there may be multiple "thresholds" in the process of formal environmental regulation affecting enterprise technology innovation, and to test whether the relationship between them has spatial heterogeneity.

Regional differences in enterprise technology innovation

In order to test the differences between formal environmental regulation and technology innovation in diverse regions, this paper investigates the technology innovation coefficients of formal environmental regulation in different provinces from the perspective of individual samples. We grouped the three regions of Eastern China, Middle of China, and Western China respectively for testing and listed the estimated results in Table 5.

As can be concluded from Table 5, the technology innovation coefficients of formal environmental regulation in provinces near Eastern China are mostly positive, which makes the Porter hypothesis gains certain empirical support in Eastern China on the whole. In

Table 5 Technology innovation coefficient estimation of formal environmental regulation

	Provinces	Coef	T statistic
Eastern China	Beijing	0.102***	6.63
	Tianjin	0.095	0.27
	Hebei	0.434*	1.92
	Liaoning	0.306***	3.51
	Shanghai	0.362	0.82
	Jiangsu	0.810***	5.10
	Zhejiang	0.563***	2.78
	Fujian	0.805***	4.34
	Shandong	− 0.265*	− 1.85
	Guangdong	0.874***	3.83
	Hainan	0.019	0.04
Middle of China	Shanxi	− 0.067	− 0.20
	Jilin	− 1.480***	− 2.90
	Heilongjiang	0.166	0.74
	Anhui	0.572***	4.73
	Jiangxi	− 0.224	− 1.23
	Henan	− 0.561	− 1.58
	Hubei	− 0.041	− 0.29
	Hunan	0.499***	4.50
Western China	Inner Mongolia	0.048	0.21
	Guangxi	1.605***	3.28
	Chongqing	− 0.961***	− 2.78
	Sichuan	0.774***	4.64
	Guizhou	− 1.474***	− 2.94
	Yunnan	0.394**	2.01
	Shanxi	0.014	0.05
	Gansu	0.998	1.02
	Qinghai	0.226**	2.12
	Ningxia	0.668**	2.45
	Xinjiang	1.807***	3.98

*, **, and *** show significance at the 10%, 5%, and 1%, respectively

addition, Shandong's FERI technology innovation coefficient is significantly negative, indicating that the implementation of formal environmental regulation in Shandong province has hindered technological innovation. As one of China's relatively developed regions, Shandong province has invested in new energy industries such as photovoltaics in recent years, which has prompted Shandong province to introduce and learn advanced foreign technologies. It can also be said that technology innovation is not entirely dependent on formal environmental regulation. In contrast, the measurement of formal environmental regulation will increase the production costs of enterprises to a considerable extent. The improvement of regulation intensity may lead to a decline in the technological innovation capacity of enterprises, especially middle- and small-sized enterprises. Formal environmental regulation in most provinces in Middle of China has hampered technological innovation in enterprises. Formal environmental regulation in Western China generally promotes technology innovation, but the FERI technological innovation coefficients in Chongqing, Guizhou, and other provinces are significantly negative. Therefore, the Porter hypothesis has no empirical support in Middle of China and Western China.

According to the above analysis results, the impact of formal environmental regulation on technology innovation has significant regional differences. As the forerunner of China's reform and opening up, Eastern China relies on its geographical advantages and policy advantages to attract more talents, thereby accumulating human capital for technological innovation. The support of national innovation policies in Eastern China is relatively strong, which will help the development of technological innovation activities of enterprises. In addition, these provinces have a relatively high level of marketization, and Chinese enterprises are facing greater innovation pressure, which can force enterprises to carry out technology innovation. With the strong support of national policies, the formal environmental regulation in Middle of China and Western China can promote the enterprise technology innovation to a certain extent. However, as these provinces face two major challenges of economic development and environmental protection, formal environmental regulation will largely squeeze out enterprise technology innovations. The production factors of capital, labor, and technology in Middle of China and Western China are relatively scarce. And enterprises engaged in technological innovation are insufficient endogenous motivation. These are not conducive to the development of technological innovation activities.

"Threshold effect" of environmental regulation on technology innovation

Panel threshold model

For the purpose of verifying the threshold effect of formal environmental regulation on technology innovation, this paper uses the panel threshold regression model presented by Hansen (1999). The advantage of the threshold model is that it can estimate the threshold value corresponding to the indicator variable, conducting endogenous grouping of samples to avoid subjective grouping. The segmentation function is constructed according to the specific threshold value, and then the "threshold effect" is tested for significance. Firstly, this paper conducts an endogenous grouping of samples from various provinces in China through threshold test, and empirically estimates and tests the threshold effect of formal environmental regulation. Secondly, the threshold model regression is carried out to test the spatial heterogeneity between formal environmental regulation and technology innovation. Based on the above model (4), we establish a threshold regression model as follows:

$$\ln I_{it} = \beta_0 + \beta_{11}\ln FERI_{it} \times I\left(q \le \gamma_j\right) + \beta_{12}\ln FERI_{it} \times I\left(q > \gamma_j\right) + \beta_2 \ln IERI_{edu,it} + \beta_3 \ln IERI_{wage,it} + \beta_4 \ln IERI_{age,it} + \beta_5 \ln IERI_{den,it} + \beta_6 \ln FDI_{it} + \beta_7 \ln IL_{it} + \beta_8 \ln IM_{it} + \beta_9 \ln PROFIT_{it} + \varepsilon_{it}$$

The meaning of the relevant variables in the above equation is the same as in Eq. (1). $I(\cdot)$ is the indicative function. If $(\cdot)$ is true, I is equal to 1; otherwise, I is 0. The variable q is the threshold variable, and γ_j is the threshold value to be estimated. When the variable q is less than or equal to the threshold γ_j, the anti-driving effect of formal environmental regulation on technology innovation is β_{11}; when the variable q is greater than the threshold γ_j, the anti-driving effect of formal environmental regulation on technology innovation is β_{12}. If there is the threshold value γ_j and passes the significance test, then the anti-driving effect of formal environmental regulation on enterprise technology innovation varies in different intervals. That is, the values or symbols of β_{11} and β_{12} will be different. This paper takes the single threshold model as an example, and the multiple threshold model can be extended on this basis.

Threshold variables and threshold effect tests

The selection of the threshold variables can be explanatory variables in the model or independent variables. The policy intensity of formal environmental regulation in different provinces is diverse, and it should also be considered that formal environmental regulation has the lagged effects on technology innovation of enterprises. Thus, this paper selects the formal environmental regulation (FERI) and its lag one term ($FERI_{t-1}$) as the alternative threshold variables. In addition, the economic development levels of the provinces also have great difference, and the differences in economic development levels have different effects on the innovative effects of formal environmental regulations. Therefore, this paper incorporates per capita GDP (Shen and Liu 2012) and its lag one term GDP_{t-1}, into the alternative threshold.

In this paper, the threshold effects of four alternative threshold variables are tested in order to determine the threshold variables and threshold number. Table 6 presents the LR statistics of different threshold test types and the P values of single, double, and triple thresholds obtained by the Bootstrap method. In Table 6, we can see that formal environmental regulation and its lag one term have passed the significance test of a single threshold. Formal environmental regulation intensity is subject to a single threshold model at 1% significance level and the corresponding bootstrap P value is 0.0000. For lagging the first phase of formal environmental regulation intensity, the bootstrap P value for a single threshold is significant at 0.0800. When the per capita GDP is used as the threshold, the single threshold model is significant at 1% level, but the bootstrap P value of the double threshold test is 0.4567, which is not significant at 10% level, so per capita GDP passes the significant test of single threshold. When per capita GDP_{t-1} is taken as the threshold variable, the single threshold and the double threshold are significant at level of 5% and 10%, respectively. The corresponding bootstrap P values are 0.0167 and 0.0967, respectively, while the test for a triple threshold is insignificant at 10% level, so the model has a double threshold effect. Therefore, this paper selects per capita GDP of the first lagging period (GDP_{t-1}) as the threshold variable, and the estimated values of two thresholds are 33,748.8 and 69,563.83, respectively. According to the relationship between the degree of economic development and the estimated threshold, 30 provinces in the study period were grouped. The results of grouping are shown in Table 7.

Table 6 Results of threshold effect tests

Threshold variables	Single threshold		Double threshold		Triple threshold	
	LR statistic	P value	LR statistic	P value	LR statistic	P value
FFERI	35.14***	0.0000	11.42	0.2767	7.61	0.7733
$FERI_{t-1}$	17.52*	0.0800	5.36	0.7800	4.14	0.8933
GDP	24.64**	0.0333	8.47	0.4567	8.37	0.6567
GDP_{t-1}	27.16**	0.0167	17.37*	0.0967	6.53*	0.6467

*, **, and *** show significance at the 10%, 5%, and 1%, respectively

Table 7 Grouping results based on threshold values

Threshold value and interval	Each group includes provinces (2016)	Sample size
$GDP_{t-1} \leq 33{,}748.8$	Anhui, Jiangxi, Guangxi, Sichuan, Guizhou, Yunnan, Gansu	7
$33{,}748.8 < GDP_{t-1} \leq 69{,}563.83$	Hebei, Shanxi, Liaoning, Jilin, Heilongjiang, Fujian, Shandong, Henan, Hubei, Hunan, Hainan, Chongqing, Shanxi, Qinghai, Ningxia, Xinjiang	16
$GDP_{t-1} > 69{,}563.83$	Beijing, Tianjin, Inner Mongolia, Shanghai, Jiangsu, Zhejiang, Guangdong	7

Threshold regression result and analysis

In this paper, the threshold regression is performed using Stata15.0 statistical software. The regression results are demonstrated in Table 8. There are significant differences in the parameter estimates of the core explanatory variables, indicating that there is a non-linear relationship between formal environmental regulation and enterprise technology innovation, and its anti-driving effect changes with the change of economic development level. At the same time, it also indicates that the impact of formal environmental regulation on enterprise technology innovation is spatially heterogeneous.

In Table 8, the anti-driving effect of formal environmental regulation intensity on enterprise technology innovation is not monotonous, and the technical innovation coefficient of formal environmental regulation is significantly different in various provinces. As per capita GDP increases from low to high, formal environmental regulations will hinder and then promote technological innovation of enterprises. When per capita GDP of the first lagging period (GDP_{t-1}) in a province is lower than 33,748.8 yuan, a 1% increase in formal environmental regulation will reduce technological innovation activities by 0.5244%. When per capita GDP of the first lagging period (GDP_{t-1}) in a province is located at interval 33,748.8 yuan and 69,563.83 yuan, the influence direction of formal environmental regulation intensity on technological innovation has changed. The technology innovation coefficient of environmental regulation changes from negative value to positive value, that is, from negative hindering effect to positive promoting effect. For every 1% increase in IERI, I will increase by 0.3411%. When per capita GDP of the first lagging period (GDP_{t-1}) in a province crosses the threshold of 69,563.83 yuan, the technology innovation coefficient of the formal environmental regulation is still positive, but compared with the previous threshold interval, the coefficient is reduced from 0.3411 to 0.1571.

According to the results of sample grouping, there are 7 provinces below the first threshold. The formal environmental regulation intensity of these 7 provinces fails to effectively drive or even hinder the technological innovation of enterprises. Since these provinces are all underdeveloped regions with insufficient economic development level, the financial strength is insufficient. On the one hand, the implementation of formal environmental regulation will enable enterprises to invest a portion of the funds to control the pollution caused by production and so on, so that the R&D investment of enterprises is dispersed. To a certain extent, it can hinder the enterprise technology innovation activities. On the other hand, due to the constraints of regional economic development, enterprises lack sufficient material conditions when engaging in research and development activities, resulting in insufficient basic support for technological innovation of enterprises, thus inhibiting technological innovation of enterprises.

Table 8 Panel threshold regression results

Variable	Coef	OLS SE	White SE
ln*FERI* ($GDP_{t-1} \leq 33{,}748.8$)	−0.5244***	0.0619	0.0702
ln*FERI* ($33{,}748.8 < GDP_{t-1} \leq 69{,}563.83$)	0.3411***	0.0513	0.0789
ln*FERI* ($GDP_{t-1} > 69{,}563.83$)	0.1571***	0.0583	0.0884
$\ln IERI_{edu}$	0.4371	0.1114	0.1374
$\ln IERI_{wage}$	0.3874	0.1780	0.1752
$\ln IERI_{age}$	−0.2423	0.3010	0.3150
$\ln IERI_{den}$	0.9347	0.8762	1.4787
ln*FDI*	−0.1250	0.0325	0.0528
ln*IL*	0.4779	0.1424	0.1993
ln*IM*	0.3451	0.1589	0.1556
ln*PROFIT*	−0.0200	0.0346	0.0411

*, **, and *** show significance at the 10%, 5%, and 1%, respectively

There are 16 provinces between the first threshold and the second threshold. The intensity of formal environmental regulation in these provinces can play a significant positive role in enterprise technology innovation. That is, the degree of economic development is conducive to promoting the technical innovation effect of formal environmental regulation. Most provinces in China are in this range, and most of them are typical industrial provinces and have abundant resources. These provinces have long relied on traditional heavy industry and highly polluting industries. Their industrial structure is in a state of solidification, and the endogenous motivation of enterprises is insufficient, resulting in the lack of talent and technology accumulation, and the urgent need to change the mode of "development with the environment." Therefore, when the economic development level of these regions is in a moderate range, the implementation of formal environmental regulations will bring pressure on enterprises to prevent and control pollution sources and governance, which effectively forces enterprises to upgrade their equipment and develop new and high technologies with low energy consumption and high efficiency.

There are 7 provinces with a lag in the economic development level crossing the second threshold. Most of these provinces are located in the economically developed eastern provinces, and their formal environmental regulation intensity can also effectively promote the technological innovation of enterprises, thus promoting the development of higher economic quality. This fully demonstrates that these provinces have achieved a win-win situation between environmental protection and economic growth, and verified the right half of the EKC curve, while the technological innovation coefficient of environmental regulation has decreased. This is mainly because the provinces with higher levels of economic development have relatively strong financial strength and have gathered many high-tech talents. Moreover, relying on the advantages of geographical location and preferential policies of the central government to engage in scientific and technological research and development activities, formal environmental regulation on technological innovation of enterprises is relatively weak.

Conclusions and policy implications

Conclusions

This paper first divides environmental regulations into formal environmental regulation and informal environmental regulation, and measures the strength of indicators. Then, using panel data of China's 30 provinces between 2009 and 2016, the panel regression analysis is used to verify the anti-driving effect of environmental regulation on enterprise technology innovation. Finally, using the panel variable coefficient regression model and the threshold regression model, the spatial heterogeneity of formal environmental regulation on enterprise technology innovation is investigated. The main conclusions of this paper are as follows. Firstly, formal environmental regulation has effectively promoted technological innovation in enterprises. Besides, informal environmental regulation can play a positive driving role in enterprise technology innovation. The education level, income level, and population density are positively related to enterprise technology innovation, and only the age structure is negatively correlated with enterprise technology innovation, which indicates that Chinese overall improvement of environmental regulation has a remarkable anti-driving effect on the increase of technological innovation in enterprises. Second, the impact of formal environmental regulation on corporate technological innovation presents significant regional differences. The Eastern China's more developed economy generally supports the "Porter hypothesis," and the Middle of China and Western China do not support the "Porter hypothesis" to a certain extent. Third, selecting per capita GDP of the first lagging period (GDP_{t-1}) as the threshold variable, the results show that the intensity of formal environmental regulation has a threshold effect on the technological innovation of enterprises. That is to say, with the gradual improvement of the degree of economic development, the technological innovation of enterprises has the effect of first suppressing and promoting: when per capita GDP of the first lagging period (GDP_{t-1}) is between the first threshold and the second threshold, and crosses the second threshold, formal environmental regulation intensity has positively promoted technological innovation of enterprises; when it is lower than the first threshold, formal environmental regulation intensity has not effectively driven the technological innovation of enterprises, and even played a hindrance role.

Policy implications

Based on the above research and findings, this paper proposes the several policy implications for governments and enterprises.

Develop appropriate formal environmental regulations

On the basis of the reality of different regions and the heterogeneity of formal environmental regulations, we should refuse to adopt an environmental regulation policy measured by a benchmark, and adopt effective and differentiated regulatory measures according to local conditions. Firstly, for provinces where formal environmental regulation has promoted technological innovation in enterprises but is not obvious, such as areas with relatively low levels of economic development in Middle of China and Western China, the intensity of formal environmental regulation in these regions should not be blindly increased, but should be guided by national major regional policies. In this way, we can create a good financing environment, increase investment in technological innovation, and provide basic conditions for technological innovation. Secondly, in the provinces where formal environmental regulation contributes to technological innovation of enterprises, such as the more developed regions in Eastern China, we should attach importance to the encourage effect of formal environmental regulation on technological innovation and adopt incentive environmental regulations such as environmental protection subsidies and emissions trading to alleviate enterprise pollution emissions. Thirdly, we must strictly control the entry barriers of the industry. While maintaining coordinated economic development, we must gradually enhance the intensity of formal environmental regulation.

Give full play to the role of informal environmental regulation in promoting technological innovation of enterprises

According to the above study, informal environmental regulation is mainly manifested by the public's awareness of environmental protection. At the present stage, the environmental awareness of Chinese citizens is relatively weak overall, and the public has insufficient supervision and attention to corporate pollution behaviors. Therefore, the government need to make efforts in the following aspects. First, the government should set up the incentive standards for informal environmental regulation behaviors and encourage the public to participate in environmental protection to a certain extent. Second, we should implement policies to support and encourage the establishment of civil environmental organizations, and give full play to the strength of civil environmental organizations. Third, expert lectures on environmental protection topics and environmental day theme activities should be organized by the government to improve the environmental awareness of the citizens. Finally, the government is supposed to gradually improve the public the supervision system of polluting manufacturers and require enterprises to truthfully disclose environmental information.

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