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RESEARCH ARTICLE

Is technological innovation the effective way to achieve the “double dividend” of environmental protection and industrial upgrading?

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Abstract
In recent years, the global emphasis on environmental protection issues has gradually increased. The existing literature has been divided on whether environmental regulation promotes or inhibits industrial development. Can the innovation-driven strategy proposed by China achieve a win-win situation for both? This paper attempts to investigate the technology innovation of China’s three major economic zones in dual environmental regulation effect on industrial structure upgrade. The research was conducted based on Intermediary Effect Model and employing the technique of Image Analysis, panel data of 30 Chinese provincial from in 2005 to 2017 were selected and analyzed. The results demonstrate that the direct effect of formal environmental regulations (ER) on industrial upgrading is an inverted “U” shape, and it is positively affecting industrial upgrading through technological innovation strategies. However, the mediating role of technological innovation under the informal environmental regulation (IER) is negative. The effect of the innovation-driven strategy has regional heterogeneity, and marketization is conducive to industrial upgrading, but increasing dependence on foreign trade is not conducive to industrial upgrading. The research above politically suggests that China should further strengthen formal and informal environmental regulations, the informal environmental regulation system should be improved, and feedback mechanisms such as laws should be established. Meanwhile, the government should carry out innovation-driven strategies based on local conditions, improve the innovation mechanism, and enhance the diffusion of technological innovation.

Keywords Formal environmental regulation · Informal environmental regulation · Industrial upgrading · Technological innovation · Mediation effect

Introduction

The economic growth of China was seen by the world ever since the opening-up policy was proposed by the government, which allows China to become the world’s second largest economy and achieved a “Chinese miracle” that attracted worldwide attention. In terms of the ecological environment, according to the data retrieved from 338 cities by the Ministry of Ecology and Environment, only 121 could meet the air quality standards, occupying less than 40% of the country’s total. In addition, China was only ranked 120th among emerging economies, as reported in the 2018 environmental performance index of 2018.The disadvantages of the factor input-driven growth model and its destructiveness to the environment are increasingly apparent (Deng et al. 2019). Environmental protection has been widely concerned by policy makers. In the past 2 years, China has implemented a series of strict environmental regulation policies to curb the deterioration of the environment: the Environmental Protection Tax Law and the Water Pollution Prevention Law began to be implemented nationwide in January 2018. This is the first time that the Chinese government has imposed an environmental protection tax on polluting enterprises. From January 1, 2018, the “Reform Plan of Ecological Environment Damage Compensation System” issued by the General Office of the State Council will try out the ecological environment damage compensation system nationwide. On January 21, 2019, the general office of the State Council issued the “Circular of the General Office of the State Council on Issuing the Pilot Work Plan for the Construction of Waste-

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free Cities." On March 6, 2019, the National Development and Reform Commission and other ministries jointly issued the "Green Industry Guidance Catalogue (2019 Edition)," the introduction of which provided "green" judgment criteria for departments to formulate relevant policies and measures. On April 1, 2019, the Ministry of Agriculture and Rural Affairs and others jointly issued the "Implementation Plan for Groundwater Pollution Prevention" and on May 30, the Ministry of Agriculture and Rural Affairs issued the "Notice on Doing a Good Job in Monitoring Agro-ecological Environment." Supporters of environmental regulation policy believe that the current environmental regulation policy is a necessary measure to protect the environment (Wang et al. 2019). Research has found that modern agricultural technology innovation is related to implementations of environmental protection, and at the same time, it can improve management and profitability (Nikolova 2015). Opponents believe that strict regulation will lead to heavier burden on enterprises, thus hindering the development of the industry (Becker 2011; Teeter and Sanberg 2017). Many regions are confronted with a balancing between industrial development and environmental protection. Innovation strategy has become an important means to stimulate economic development and promote the transformation and upgrading of industry. The technological innovation effect of environmental regulation is of great significance to realize long-term economic development. At the same time, to promote the transformation and upgrading of industrial structure, it is necessary to improve the support of scientific and technological innovation. From this, we can see that there is an internal connection between the three, so is technological innovation an effective way to achieve a win-win situation between environmental protection and industrial upgrading? At the present stage, the pollution has attracted the attention of public groups that have participated in environmental protection, and the exposure of major pollution events through media was also blamed for having negatively affected the corporate reputation building and social image of the company. Such informal environmental regulations are also playing an increasingly important role in environmental protection, attracting more and more attention from scholars (Langpap and Shimshack 2010; Xie et al. 2017; Ren et al. 2018). Compared with the government's formal environmental regulation, informal environmental regulation differs greatly in terms of functionary mechanism and extent of effect; therefore, it has different impacts on the technological innovation behavior of enterprises. The existing research perspective seldom deals with the impact of environmental regulation on industrial upgrading. Based on this, this paper uses the mediation effect model to examine the direct impact of formal and informal environmental regulations on industrial upgrading and the indirect impact of the intermediary effect of technological innovation.

The rest of this paper is arranged as follows: the second part reviews the previous scholars' studies. The third part is the mathematical derivation of environmental regulation promoting industrial upgrading at the micro level. In the fourth part, we introduce the mediating effect model and index construction. The fifth part carries on the total sample and the empirical analysis by region. Finally, the sixth part completes the summary and the policy enlightenment.

Literature review

The current literature on the relationship among environmental regulation, technological innovation, and upgrading of industrial structure can be divided into four directions:

First is the environmental regulation and technological innovation. The conclusions drawn from the research regarding the two aspects can be divided into the following three points of view. (i) Inhibition effect: environmental regulation increases the production cost of manufacturers, weakens technological innovation, and supports the "compliance cost" theory (Jaffe et al. 1995; Chintrakarn 2008; Ramanathan et al. 2010). To achieve the environmental standards, the major approach adopted by enterprises is upgrading the pollution control equipment and production equipment, rather than through technological innovation (Zhang and Lv 2018). (ii) Promoting effect: Porter and Linde (1995) first proposed the "Potter hypothesis" believing that reasonable environmental regulation would promote innovation and enhance the competitiveness of enterprises. Many scholars have found that environmental regulation could to some extent promote technological innovation of enterprises (Brunnermeier and Cohen 2003; Hamamoto 2006; Yang et al. 2012). Reasonable environmental regulation will encourage enterprises to carry out technological innovation (Kammerer 2009; Lanoie et al. 2011; Song et al. 2019). (iii)There is a non-linear relationship between the two. Some scholars used provincial panel data to study the role of environmental regulation on green technology innovation and concluded that the relationship of them could be represented in a diagram with a pattern of "*U*" (Yuan et al. 2017). Only when the environmental regulation intensity crosses the threshold value can it promote technological innovation (Yuan and Li 2018).

Second, some studies have found that technological innovation helps to optimize the industrial structure (Verbano and Crema 2016). Innovation activities can promote different industries into high-productivity growth industries, thus optimizing the entire industrial structure (Varum et al. 2009; Zhang and Gallagher 2016). Some scholars believe that the transformation of manufacturing industry must be driven by innovation (Lager 2016). The change of demand structure brought by innovation and the improvement of labor productivity are the main reasons driving the upgrading of industrial structure (Tao and Peng 2017).

Third is environmental regulation and industrial structure upgrading. Some scholars point out that when the technical effect of environmental regulation is stronger than the distortion effect of resource allocation, environmental regulation will promote the upgrading of industrial structure (Liu et al. 2016). Other scholars use theoretical models to describe the mechanism of environmental regulation on industrial transformation and upgrading (Berman and Bui 2001). Environmental regulation has significantly forced polluting enterprises to transform and upgrade their industries, but only for non-state-owned enterprises, and it is difficult for state-owned enterprises to transform and upgrade (Greunz 2004). However, the existing literature overwhelmingly stresses on focus on the impact of environmental regulation on productivity; therefore, the strengthening of the environmental regulation was believed to be an effective approach to an increased productivity (Berman and Bui 2001). Another view is that, although environmental regulation can help the development of environmentally friendly technologies, the benefits cannot offset the burden of increased production costs. Pollution costs will crowd out production costs and reduce productivity levels (Gray and Shadbegian 2003), when environmental regulations are stricter, and in order to produce more products at the same level of pollution per product, enterprises will have to upgrade the facilitates in order for an increased production, or increase technological research and development of relevant alternative energy, thus hindering the industrial upgrading of the whole economic system (Feichtinger et al. 2005). Different from former conclusions, some scholars have concluded that the impact of environmental regulation intensity on industrial transformation and upgrading depends on the relative size of economic output of pollution-intensive industries and clean industries, thus concluding that environmental regulation and industrial upgrading have j-shaped characteristics (Tong et al. 2016). Other studies have concluded that there is an inverted u-shaped relationship between environmental regulatory intensity and environmental total factor productivity (Wang and Shen 2016).

Fourth, researches on technological innovation, environmental regulation, and industrial structure upgrading exhibit that only when technological innovation crosses the threshold can the synergistic effect of environmental regulation and technological innovation positively promote industrial structure upgrading (Maochu Zhong et al. 2015). However, the literature that gives insights into industrial structure upgrading was rare, and the aspects addressed within the most relevant articles were mainly industrial ecological efficiency and industrial performance (Baolong Yuan et al. 2017; Korhonen et al. 2015).

Most of the previous studies focus on the relationship between the two and use threshold model to study the appropriate range of environmental regulation. The existing empirical research conclusions on environmental regulation, technological innovation, and environmental regulation are quite different, which may be caused by the following aspects. First of all, different countries and different regions have different environmental regulatory objectives and tools at different times, and the policy impacts analyzed based on them are certainly different. Second, there is a large gap between different regions in economic development level, industrial structure, resource endowment, and factor input structure among enterprises and industries, which determines the huge difference in environmental regulation's impact on industrial structure adjustment among different regions. Finally, the index selection and model selection of environmental regulation usually have individual subjective tendency of researchers. In recent years, informal environmental regulations with the public, media, and environmental protection organizations as the main body play an increasingly important role in environmental protection. Some scholars simply added the interaction item between environmental regulation and technological innovation and concluded that innovation did indeed play a regulating role in environmental regulation and industrial structure adjustment but did not deeply analyze the difference and reasons of intermediary role in technological innovation in different regions.

Theoretical analysis and transmission mechanism

Theoretical analysis

The influence of environmental regulation on industry is to influence the production decision-making behavior by affecting the prices of different production factors of enterprises. Under different environmental regulations, the production factor costs of the same manufacturer producing clean products and polluting products are affected differently. Reference Withers (1980), the method of assuming that A and B both have totally the same vendors, including one of vendors only product polluting production and cleaning products, the price of factors of production is w and n. The selling prices of polluting products are P_1 and P_2 respectively in regions A and B. The sales volume of these two products is Q_1 and Q_2respectively. The selling price of cleaning products is L and the sales volume is S. Suppose that the input of other factors (labor, capital, etc.) is k, α is the distribution coefficient of factor input into polluting products, with a value of 0 to 1. Since the products from region A to region B will incur inevitable transportation, loss and other costs, set a cost adjustment factor which is γ, then when the selling price of polluting products in region A is P_1, then the selling price in region B is γP_1, The profit of the manufacturer is

$$\pi = p_1 \cdot Q_1 + \gamma \cdot p_2 \cdot Q_2 + L \cdot S - [w\alpha + n(1-\alpha)]K \qquad (1)$$

When there is a difference in the degree of environmental regulation between A and B, let us assume that A is stricter. In this case, clean products are not affected much, and the price of production factors of polluting enterprises becomes W_1. If the manufacturer does not take any measures, the profit becomes

$$\pi = p_1 \cdot Q_1 + \gamma \cdot p_2 \cdot Q_2 + L \cdot S - [w_1\alpha + n(1-\alpha)]K \qquad (2)$$

If the enterprise decides to change its production strategy and put more production materials into the production of clean products, this is the enterprise's behavior of pursuing profits, but it has virtually promoted the upgrading of the entire industrial structure. The distribution coefficient of the enterprise after the change of production strategy is denoted as α_1, and α_1 is smaller than α, because the input of production means of polluting products is reduced due to the influence of environmental regulations. At this point, the sales volume of polluting products and cleaning products becomes $Q_1^{'}$ and $Q_2^{'}$ respectively. The sales volume of cleaning products is $S^{'}$, and the profit of the manufacturer is

$$\pi = p_1 \cdot Q^{'}_1 + \gamma \cdot p_2 \cdot Q^{'}_2 + L^{'} \cdot S^{`} - \left[w_1\alpha^{'} + n\left(1-\alpha^{'}\right)\right]K \qquad (3)$$

According to the profit maximization principle, if the manufacturer wants the profit after the optimized production to be larger than the profit before the adjustment, the following equation can be obtained:

$$W_1 > n + \frac{p_1\left(Q_1^{'}-Q_1\right) + \gamma P_2\left(Q_2^{'}-Q_2\right) + L\left(S^{'}-S\right)}{K\left(\alpha^{'}-\alpha\right)} \qquad (4)$$

If the price of polluting production factors after strengthening the degree of environmental regulation meets the above equation, enterprises will increase their profits by investing more production resources in cleaning products, and it is a more reasonable choice to reduce the production of polluting products. Product upgrading not only improves the profit of enterprises, but also virtually promotes the upgrading of the entire industrial structure.

Transmission mechanism

Environmental regulation and industrial structure upgrading

The direct influence of environmental regulation on industrial structure is upgrading. When environmental regulation is less effective within a society, the power of it in supervising the industry could be limited. In the early stage of regulation, enterprises have to bear negative external social costs caused by environmental pollution, resulting in increased production costs, reduced competitiveness, and decreased production efficiency(Albrizio et al. 2017). High environmental regulations even can cause the "revenge" production of polluting industries, stimulate the high pollution industry to expand production scale, "small, dirty, scattered and disorderly" companies expect the benefits increased by enlarging production scale, or pass the cost on to consumers, to offset the environmental regulation cost increase; this kind of circumstance of environmental regulation is of limited beneficial to upgrade of industrial structure (Yuan and Xie 2014). As the degree of environmental regulation improves, the supervision of various parties will be stricter, and the production environment standard of enterprises will be improved (Ollinger and Fernandez-cornejo 1998). At this time, the effect of "survival of the fittest" will be generated. Strict environmental regulation is an effective reverse mechanism to force the optimization and upgrading of industrial structure. On the one hand, higher environmental standards are equivalent to a green entry barrier, increasing the sunk cost of polluting enterprises to enter (Blairb and Hite 2005;Rubashkina and Galeotti 2015). On the other hand, under strict environmental regulations, the comparative advantages of clean industries are obvious. With the support of the government, more material capital and human capital from the society will be attracted to them, and the number of enterprises in clean industries represented by the service industry will be increased (Zheng 2018;Teeter and Sandberg 2017), which is conducive to the upgrading of industrial structure.

Environmental regulation and technological innovation

In the early stage, when the government formulated environmental regulation policies were newly formulated, the regulation intensity was less strong owing to the influence of regional economic development status, policy perfection and other factors, and the cost increase for enterprises was lower than the research and development investment needed for technological innovation. Based on cost-benefit principle, enterprises choose to pay sewage charges or terminal treatment. At this time, environmental regulations not only fail to stimulate enterprise innovation but also increase the social cost of enterprises and crowd out the funds for technology research and development, which is not conducive to enterprise innovation (Li and Mu 2013). On the other hand, as environmental regulations gradually become stricter, the impact of environmental regulations has changed from "compliance cost effects" to "innovation compensation effects." Along with more strict environmental regulation intensity, enterprises face the cost of the pollution treatment approaches or exceed the cost of the technology research and development, innovation has become profitable, enterprise's response to environmental regulation gradually from obedience to active innovation (Liu 2016), high intensity of environmental regulation to promote enterprise-independent research and development at this time or the introduction of new technology, to ensure its sustainable development (Porter and Linde 1995). At the same time, after the early accumulation and positive innovation behavior, the "innovation compensation" effect has gradually emerged (Marco et al. 2017). Technological innovation is an important driving force for the upgrading of industrial structure. When the new technology emerges, it can effectively eliminate the backward production capacity within the industry, and when it is put into application, it can promote the emergence of new technologies, products, and processes in the external-related industries. On the other hand, the emergence of new technology has improved the quality of required raw materials, forcing all relevant industries to develop to a higher level. No matter whether other factors change or not, the improvement of technological innovation level can effectively promote the transformation of industrial structure (Shi and Zhao 2018).

According to previous relevant studies, some other factors also have a significant impact on the upgrading of industrial structure:

1. Marketization helps to improve the efficiency of resource allocation and provides a good external environment for the upgrading of industrial structure.
2. Foreign direct investment. The advanced production technology and management experience brought by foreign direct investment promotes the upgrading of domestic industrial technology and contribute to the progress of industrial structure.
3. Urbanization intends to accelerate industrial agglomeration and factor agglomeration, deepen industrial restructuring and division of labor, improve industrial technology complexity and innovation level, and lead to changes in industrial structure through affecting employment structure.

Research methods, models, and data

Mediating effect

Mediating variable is the medium through which independent variable influences dependent variable. If X influences Y through variable M, then M is the mediating variable between them. Mediating effect refers to the degree to which independent variable influences dependent variable through mediating variable:

$$Y = cX + e_1 \tag{5}$$

$$M = aX + e_2 \tag{6}$$

$$Y = c^{'}X + bM + e_3 \tag{7}$$

The coefficient C in Eq. (5) is the total effect of independent variable X on dependent variable Y, the coefficient a in Eq. (6) is the effect of independent variable X on the mediating variable M, the coefficient b in Eq. (7) is the effect of mediating variable M on dependent variable Y after controlling independent variable, and the coefficient $C^{'}$ is the direct effect of independent variable X on dependent variable Y. The method of stepwise regression coefficient is commonly used to test the mediating effect.

Research model

Based on the above theoretical analysis and the mediating effect method, according to the previous analysis, it can be found that environmental regulation may have a non-linear relationship between technological innovation and industrial upgrading, so we introduce the quadratic term of environmental regulation into the model (Chen et al. 2019). And considering the environmental regulation, technological innovation, market opening index, foreign investment, and urbanization rate, the mediating effect equation of technological innovation is set as follows:

$$Ind = \partial + \partial_1 Er_{it} + \partial_2 (Er_{it})^2 + \partial_3 Mdi_{it} + \partial_4 Fdi_{it} + \partial_5 Urban_{it} + \delta_{it} \tag{8}$$

$$RD = \partial + \partial_1 Er_{it} + \partial_2 (Er_{it})^2 + \partial_3 Mdi_{it} + \partial_4 Fdi_{it} + \partial_5 Urban_{it} + \beta_{it} \tag{9}$$

$$Ind = \eta + \eta_1 Er_{it} + \eta_2 (Er_{it})^2 + \eta_3 RD + \eta_4 Mdi_{it} + \eta_5 Fdi_{it} + \eta_6 Urban_{it} + \mu_{it} \tag{10}$$

Variable definition and data sources

Explained variable: industrial structure index (IND)

Industrial structure adjustment means that the government rationalizes and elevates the industrial structure through corresponding industrial policies. Advanced industrial structure—the performance of industrial structure upgrading in the national economy is that the industrial proportion is gradually transferred in the order of primary industry, secondary industry, and tertiary industry. At present, the service trend of economic structure has become one of the important manifestations of industrial structure upgrading.

Based on the ideas of Yuan Yijun and Xie Ronghui (Yuan and Xie 2014), this paper chooses "the ratio of the added value of the tertiary industry to the added value of the secondary industry" to reflect the upgrading status of China's industrial structure.

Explanatory variables: formal ER and IER

Formal environmental regulation (ER). At present, there is no unified standard for the measurement of formal environmental regulation. This paper uses the construction of environmental regulation evaluation index method (Jiang and Zhao 2019), which not only includes the actual investment of industrial pollution control in each province but also removes the deviation caused by regional industrial structure factors. The construction process is as follows:

$$COST_{i.t} = \frac{Invest_{it}}{Industry_{it}} \tag{11}$$

$COST_{i.\ t}$ represents the pollution control cost in each province of China, i = 1, ..., 30 indexes provinces in China,t = 2005, ..., 2017 indexes time. $Invest_{it}$ indexes investment in industrial pollution control. $Invest_{it}$ represents the industrial output value of province i in year t. Without considering the differences in industrial structure between regions, the calculated pollution control cost of industrial output will overestimate the environmental regulation intensity of pollution-intensive provinces and correspondingly underestimate the environmental regulation intensity of non-pollution-intensive provinces. Therefore, it needs to be revised according to the proportion of the total industrial value of each region in the GDP of each region:

$$ER_{i.t} = \frac{COST_{i.t}}{\mathrm{Pro}_{it}} \tag{12}$$

Pro_{it} represents the ratio of the total industrial production value divided by the total regional production value. $COST_{i.\ t}$ represents the pollution control cost in each province of China.

Informal environmental regulation (IER) was first proposed by Pargal and Wheeler (1996), which refers to negotiations or consultations between the public, media, and social groups and polluting enterprises in order to achieve pollution reduction and environmental protection, including issuing a lawsuit and complaints of residents and protests against polluting enterprises, which is an effective supplement to formal environmental regulation. Referring to the method of Pargal and Wheeler (1996), select three dimensions of income level, education level, and population density in each province to measure informal environmental regulation. (i) Per-capita income: In general, the higher the income of people, the higher the attention they pay to the quality of local living environment, and the higher the demand for high-quality surrounding environment. (ii) Education level: According to the number of higher education students per 100,000 population, people with higher education level are more sensitive to environmental pollution problems, and local enterprises will adopt more communication channels when environmental problems arise, which is more conducive to local environmental governance. (iii) Population density: The number of people at the end of the year divided by the area of each province is selected to measure it. When environmental pollution problems occur in local enterprises, the more people involved in the surrounding population, the stronger the environmental awareness of people's unity and resistance (Tables 1).

Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) is used to assign corresponding weights to individual indexes of informal environmental regulation, and the index is constituted as the comprehensive evaluation index of environmental regulation. The specific treatment method is as follows:

1. Normalization of index matrix. The indicators in this paper are all positive indicators. Then, conduct standardized treatment:

$$X'_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})}$$

where x_{ij} and x'_{ij} denote the informal environmental regulation measurement index of province $_i$ and dimension j before and after standardization respectively.

2. Determining information entropy:

$$\mathrm{p_{ij}} = X'_{ij} / \sum_{i=1}^{\mathrm{n}} X'_{ij}$$

and

$$H_{\mathrm{j}} = \ln\frac{1}{\mathrm{n}} \sum_{i=1}^{n} \left(p_{ij} * \ln p_{ij}\right)$$

where p_{ij} denotes the characteristic weight of dimension j in province i.

3. Weight of measuring indicators:

$$W_{\mathrm{j}} = \left(1 - H_j\right) / \sum_{j=1}^{m} \left(1 - H_j\right)$$

4. Calculate the comprehensive score of each sample:

Table 1 Weight of indicators of informal environmental regulation

Variable	Context	Weight
Per capita income	The average salary of employees employed by urban units in various regions	0.160
Education level	Per 100,000 population of students in higher education	0.193
Population density	The ratio of the total number of people to the area of each province at the end of the year	0.647

$$s_i = \sum_{j=1}^{m} w_j * x_{ij}$$

Intermediary variable: technological innovation (R&D)

Previous studies mostly used the number of patent applications or R&D investment (Baolong Yuan and Chen Li,2018) as an indicator of the level of technological innovation. This paper used the logarithm of the number of patent grants in various regions as an indicator of technological innovation.

Other control variables: marketization degree (MDI) is expressed by marketization index. Foreign direct investment (FDI) is expressed by the ratio of the value of foreign direct investment of each province to the gross regional product. Urbanization (URBAN) level is measured by the proportion of urban population in the total population of each province.

Data sources and descriptive statistics

Due to the availability of data, this paper selected the remaining 30 provinces, autonomous regions, and municipalities except Tibet autonomous region, Hong Kong, Macao, and Taiwan regions of China for empirical testing. In addition, the data retrieved were existing records in China statistical yearbook, China statistical yearbook of industrial economy, China environmental yearbook, China environmental statistical yearbook, China statistical yearbook of science and technology, and China energy yearbook from 2005 to 2017. The marketability index data from 2005 to 2007 were obtained from China marketization index—relative progress of marketization in each region 2011 report by Fan Gang, Wang Xiaolu, and Zhu Hengpeng, and the data from 2008 to 2016 were obtained from China marketization index report by provinces (2018), and the missing data were filled in by interpolation. According to the division of China's real estate development, investment, and sales in 2016 released by the statistics bureau in January 2017, the eastern region includes 11 provinces (cities) including Beijing, Tianjin, Hebei, Liaoning, Shanghai,Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan. The central region includes eight provinces: Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, and Hunan. The western region includes 12 provinces (municipalities and autonomous regions) of Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Xizang, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang. Table 2 is the descriptive statistics on variables.

Empirical analysis

Overall regression analysis

In Table 3, Eq. (1) tests the overall effect of formal environmental regulation on industrial structure upgrading. The coefficients of the primary and secondary terms of formal environmental regulation intensity in the model are positive (0.179) and negative (− 0.0213), respectively. It shows that with the increase of the intensity of formal environmental regulation, the impact on the upgrading of industrial structure presents an inverted U shape, contrary to the results of some scholars (Wang and Shen 2016; Liu et al. 2016). The reason for the different research results may be that there are many tools for environmental regulation, different scholars have a subjective tendency in constructing environmental regulation indicators, and the effects of environmental regulation in different regions are also different. Kong and Zhang (2017) also obtained an inverted U-shaped relationship when they used the proportion of pollution control investment as the environmental regulation index to analyze the impact on industrial upgrading. Equation (2) is the influence of formal environmental regulation on technological innovation as an intermediary variable. The coefficients of the primary and secondary terms are negative (− 0.146) and positive (0.0151), respectively. In other words, the influence of formal environmental regulation on technological innovation shows a U shape, which is first

Table 2 Descriptive statistics

Variable	Obs	Mean	Sd.	Min	Max
IND	390	0.986	0.540	0.500	4.237
IER	390	2.527	159.039	1.994	10.537
ER	390	1.122	104.710	1.4.57	7.926
R&D	390	9.185	1.613	4.369	12.715
MDI	390	6.355	1.813	2.330	10.920
FDI	390	0.024	0.019	0.010	0.082
URBAN	390	52.941	13.966	26.870	89.600

Table 3 Regression results of mediating effect

	Formal environmental regulation			Informal environmental regulation		
Variables	(1) IND	(2) R&D	(3) IND	(4) IND	(5) R&D	(6) IND
ER	0.179*** (0.0279)	− 0.146** (0.0644)	0.185*** (0.0273)			
ER^2	− 0.0213*** (0.00438)	0.0151 (0.0102)	− 0.0219*** (0.00427)			
IER				− 0.127*** (0.0388)	0.729*** (0.0767)	0.160*** (0.0424)
IER^2				0.0115*** (0.00320)	− 0.0297*** (0.00632)	0.0104*** (0.00324)
R&D			0.105*** (0.0252)			− 0.0501* (0.0265)
MDI	0.0677*** (0.0145)	0.0926*** (0.0327)	0.0628*** (0.0143)	0.0731*** (0.0130)	0.0963*** (0.0259)	0.0773*** (0.0131)
FDI	− 4.491*** (1.055)	− 13.54*** (2.362)	− 3.546*** (1.059)	− 2.016** (0.929)	− 2.980 (1.858)	− 2.129** (0.928)
URBAN	0.0172*** (0.00218)	0.125*** (0.00477)	0.00208 (0.00418)	− 0.00900** (0.00386)	0.0697*** (0.00755)	− 0.00511 (0.00438)
Constant	− 0.396*** (0.152)	2.410*** (0.307)	− 0.560*** (0.157)	0.624*** (0.155)	3.377*** (0.294)	0.780*** (0.176)
Observations	390	390	390	390	390	390
Number of ID	30	30	30	30	30	30

Standard errors in parentheses: ***$p < 0.01$; **$p < 0.05$; *$p < 0.1$

inhibited and then promoted. The early stages of the environmental regulation will have technology innovation; "crowding out" is not conducive to technological innovation, but with the increase of degree of environmental regulation, enterprises will realize that only through innovation can they achieve environmental standards to meet the market conditions, and the innovation of power is increased, but the secondary coefficient is not significant, and formal environmental regulation on technical innovation of "porter hypothesis" needs to show up under certain constraints. In Eq. (3), the regression coefficients of formal environmental regulation and technological innovation passed the significance test at 1%, indicating that there was a partial intermediary effect. It is concluded that formal environmental regulation has a direct impact on industrial structure upgrading and an indirect impact through technological innovation variables.

In Table 3, Eq. (4) examines the overall effect of informal environmental regulation on industrial structure upgrading, and it can be seen that the coefficients of the primary and secondary terms of informal environmental regulation are negative (− 0.127) and positive (0.0115), respectively, indicating a U type relationship. When the intensity of informal environment regulation is weak, companies are under less external pressure, but when regulation intensity continues to increase, the pressure from regulators such as media and the public prompts companies to reform or innovate, thereby promoting industrial upgrading. Equation (5) tests the regression results of informal environmental regulation on technological innovation as an intermediary variable. The result shows that the coefficients of the primary and secondary terms of informal environmental regulation are positive (0.729) and negative (− 0.0297), respectively, and they are in an inverted U-type relationship. In the early days of informal environmental regulation, the masses mainly promoted the technological transformation and innovation of enterprises through verbal reflection, negotiation, and other means. As the later stage became stricter, the cost of the enterprise rose sharply, affected the enterprise normal production gradually, and some smaller, low-innovation ability of enterprise's survival is affected and even bankruptcy. The extreme interpretation of environmental pollution events by the media seriously damages the social credibility and image of enterprises. It can be seen that moderate informal environmental regulation can promote enterprises' innovation, but after a certain peak, it will hinder enterprises' innovation and even affect their survival. According to the regression results of control variables, the market index has a positive effect on industrial structure upgrading and innovation. The higher the market index is, the more effective the market will be in resource allocation. Good market development atmosphere is conducive to industrial upgrading and technological innovation. And opening up to the level of technological innovation and upgrading of industrial structure are the influences of the negative effect, more shows in the foreign trade in our country at present stage is the role of processing chain, still mainly processing is given priority to, the scale of trade mode, high pollution, high energy consumption, foreign companies entering the inhibition of the upgrading of industrial structure in our country; this conclusion supports the "pollution haven" hypothesis. According to Eqs. (2) and (5), it is found that foreign investment hinders technological innovation, and foreign investment produces "crowding out effect" and "technology control effect," With advanced technology, enterprises from market abroad obtain great market share in a fairly short time and monopolized some critical industries. Foreign enterprises controlling shares and technological advantages in domestic enterprises hinder domestic enterprises' technological research and development. Urbanization rate has no significant impact on the upgrading of industrial structure, but it can promote technological innovation. This is because the improvement of urbanization will bring about the spatial agglomeration of production factors, and the agglomeration of factors will lead to the phenomenon of technology spillover, which is conducive to independent innovation. The impact of the urbanization rate on the upgrading of the industrial structure is not significant. It may exert impact on industrial structure upgrade in both positive and negative ways. As impetus, urbanization can provide high-end production factor supply, demand orientation, and improvement over service (Michaels et al. 2008). As resistance, the process of urbanization leads to dis-economy of scale and urban disease problem. Some developing countries promote the process of urbanization with extensive development methods, hindering the upgrading of national industrial structure (Farhana et al. 2014). So, the eventual impact should be judged on the basis of considering both influence of impetus effect and resistance effect.

Figure 1 depicts the trajectory of the total effect and direct effect of formal environmental regulations on industrial upgrading. Since the longitudinal intercept term does not affect the opening and shape of the image of the equation, the two images are shifted up equidistant to facilitate observation. The mediating effect is the remainder of the total effect minus the direct effect, so it will not be affected. The scale of total effect and direct effect is based on the left primary axis, and the scale of intermediate effect is based on the right sub-axis. Under formal environmental regulation of the same degree, the total effect is higher than the direct effect. Under formal environmental regulation, the intermediate effect of technological innovation is positive. It shows that formal environmental regulation can force enterprises to carry out technological innovation, and the two can achieve benign interaction. Enterprises have the motivation to carry out technological innovation and transformation of achievements, and at the same time, the industry will transform to green and advanced.

Figure 2 depicts the informal environmental regulation affects the total effect of industrial upgrading and the trajectory direct effect; the total effect of informal environmental regulation is less than the direct effect, which leads to negative mediation effect; and informal environmental regulation and technology innovation could not form the benign interaction and have a negative impact on industrial upgrading, while the public's environmental awareness has increased, but the present stage of informal channels of environmental regulation feedback mechanism is not perfect, and informal environmental regulation is very difficult to work effectively.

Regional regression analysis

Equations (1)–(6) in Table 4 are the regression results of innovation mediation effects under formal and informal environmental regulations in the eastern region, and Eqs. (7)–(12) are the regression results in the central region. The mediating effect of environmental regulation on industrial upgrading in these two regions is both valid. Under formal environmental regulation, the mediating effect of technological innovation is positive, while under informal environmental regulation, the mediating effect of technological innovation is negative.

According to zhe results from Figs. 3, 4, 5 and 6. Figure 7 compares the direct effects of technological

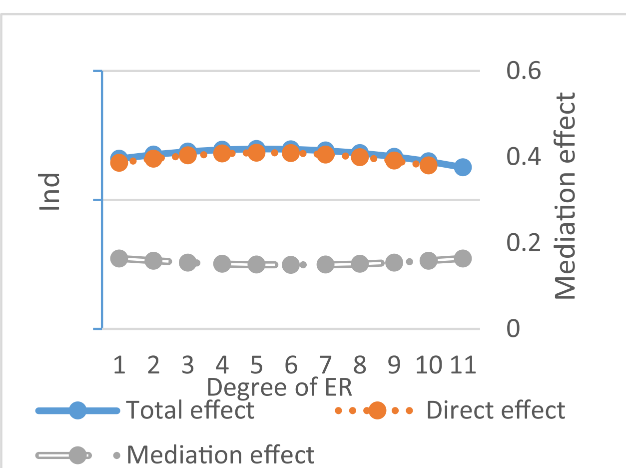

Fig. 1 Full sample mediating effect (ER)

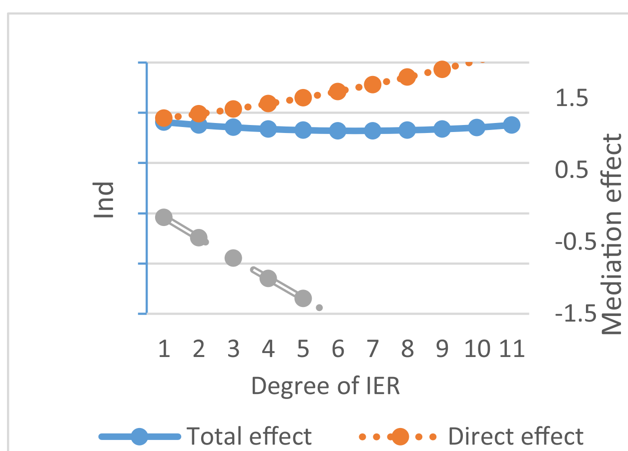

Fig. 2 Full sample mediating effect (IER)

Table 4 Regression results of mediating effect in eastern region and central region

	Eastern region						Central region					
	Formal environmental regulation			Informal environmental regulation			Formal environmental regulation			Informal environmental regulation		
Variables	(1) IND	(2) R&D	(3) IND	(4) IND	(5) R&D	(6) IND	(7) IND	(8) R&D	(9) IND	(10) IND	(11) R&D	(12) IND
ER	0.217*** (0.0536)	− 0.276*** (0.0967)	0.241*** (0.0508)				0.433*** (0.0998)	− 0.425* (0.228)	0.430*** (0.103)			
ER^2	− 0.0234*** (0.00906)	0.0359** (0.0163)	− 0.0273*** (0.00849)				− 0.0978*** (0.0364)	0.114 (0.0822)	− 0.0979*** (0.0374)			
IER				0.154*** (0.0561)	0.706*** (0.109)	0.157** (0.0617)				0.530** (0.226)	0.261 (0.367)	0.548** (0.216)
IER^2				0.0101** (0.00424)	− 0.0268*** (0.00822)	0.0101** (0.00433)				− 0.141** (0.0668)	0.137 (0.111)	− 0.105* (0.0638)
R&D			0.170*** (0.0404)			− 0.0107 (0.0419)			0.0119 (0.0327)			− 0.147*** (0.0522)
FDI	− 5.222*** (1.523)	− 17.92*** (2.775)	− 2.750* (1.601)	− 3.702*** (1.125)	− 7.315*** (2.199)	− 3.727*** (1.155)	− 4.569 (3.222)	5.832 (7.646)	− 3.794 (3.115)	0.671 (4.003)	9.437 (6.895)	2.112 (3.723)
MDI	0.0413* (0.0245)	0.139*** (0.0443)	0.0283 (0.0234)	0.0552*** (0.0167)	0.0991*** (0.0332)	0.0554*** (0.0172)	0.115*** (0.0314)	0.133* (0.0735)	0.115*** (0.0324)	0.219*** (0.0452)	0.0231 (0.0725)	0.220*** (0.0433)
URBAN	0.0201*** (0.00416)	0.0979*** (0.00767)	− 2.94e-05 (0.00595)	− 0.0169*** (0.00584)	0.0536*** (0.0109)	− 0.0157** (0.00654)	0.0188*** (0.00342)	0.159*** (0.00808)	0.0166*** (0.00533)	0.0168** (0.00795)	0.0695*** (0.0161)	0.0214*** (0.00682)
Constant	− 0.384 (0.293)	3.679*** (0.544)	− 0.839** (0.326)	1.249*** (0.293)	4.258*** (0.511)	1.271*** (0.327)	− 0.973*** (0.228)	0.488 (0.559)	− 0.986*** (0.227)	− 1.772*** (0.650)	4.052*** (1.158)	− 0.921 (0.666)
Observations	182	182	182	182	182	182	104	104	104	104	104	104
Number of id	14	14	14	14	14	14	8	8	8	8	8	8

Standard errors in parentheses: *** $p < 0.01$; ** $p < 0.05$; * $p < 0$

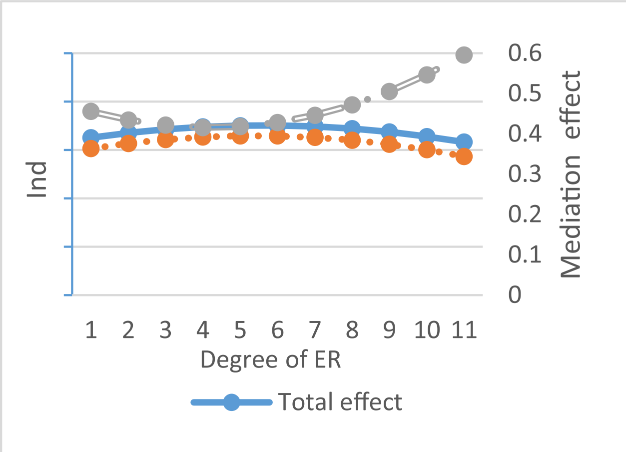

Fig. 3 Eastern region mediating effect (ER)

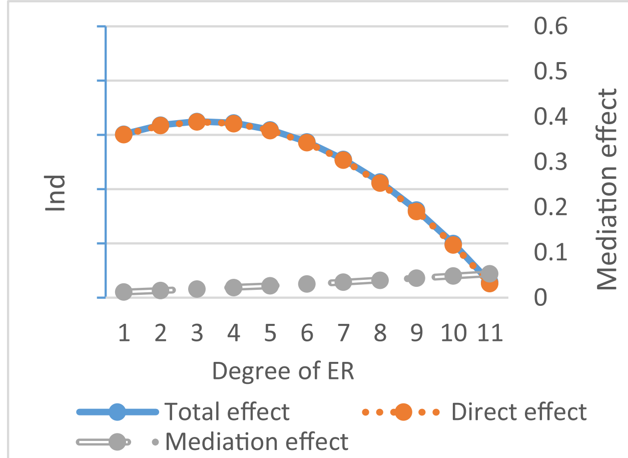

Fig. 5 Central region mediating effect (ER)

innovation in the east and the middle of China. The intermediary effect of technological innovation in the east is significantly higher than that in the middle of China, and the improvement speed is obviously accelerated when the environmental regulation intensity reaches a certain threshold. Technology innovation is the core of the development of emerging industries, but without technology diffusion, innovation cannot have an economic impact. In the eastern region, infrastructure is relatively sound, innovation mechanism is more sound, and the spillover effect of technology innovation is more obvious, and its positive promoting effect is more obvious.

Figure 8 shows the mediating effect of technological innovation in China, the eastern region, and the central region under the informal environmental regulation. From the space category of the central region to the whole country and then to the eastern region, the negative mediating effect of technological innovation decreases gradually and has the trend of rising to be positive. It shows that although China's informal environmental regulation fails to promote industrial upgrading through technological innovation at the present stage, with the improvement of social legal mechanism, the increase of informal environmental regulation channels, and the establishment of feedback mechanism, the intermediary effect of technological innovation is gradually changing.

Table 5 is the intermediary effect test results of western region, in a formal environmental regulation under environmental regulation on industrial structure upgrade failed to pass the test of significance of regression coefficient and the total effect inspection did not pass, and formal environmental regulation on technical innovation of regression coefficients were not significant, too, that a formal environmental regulation in the western region under the mediation effect, and informal environmental regulation of the regression coefficient of technology innovation is not significant.

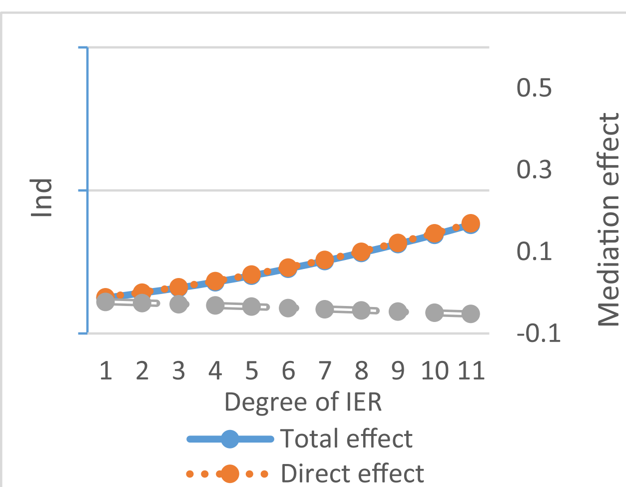

Fig. 4 Eastern region mediating effect (IER)

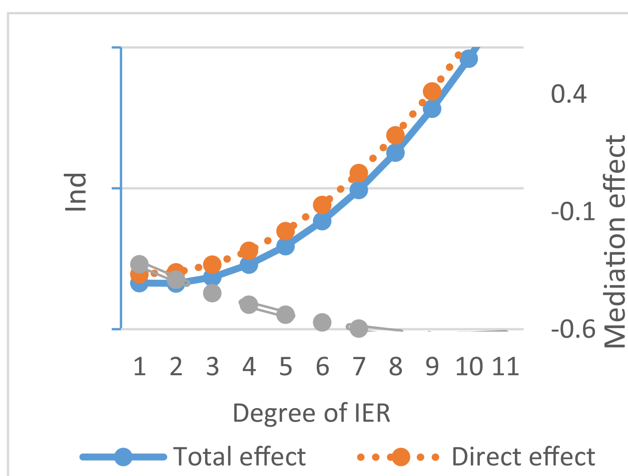

Fig. 6 Central region mediating effect (IER)

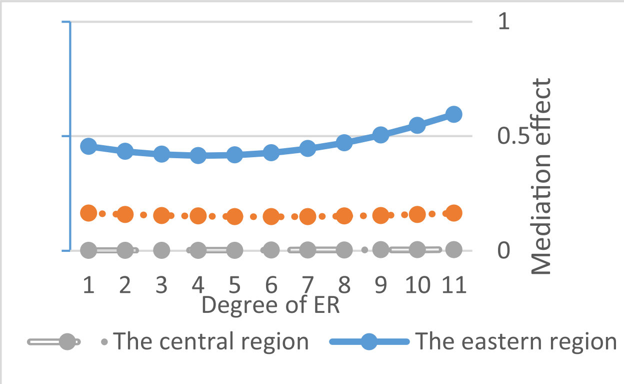

Fig. 7 Formal environmental regulations

Robustness test

Data robustness test

In order to investigate the stability of the estimated results, this paper replaced the number of invention patent authorizations with the investment of R&D funds as the index of innovation investment and tested the relationship among environmental regulation, technological innovation, and industrial structure upgrading again. The results obtained were basically consistent with the direction and size of the coefficient obtained above (Tables 6 and 7).

Model robustness test

Considering the actual economic development, the variables have different degrees of correlation, the main variables in this article may also have a two-way causality. In addition, changes in industrial structure often have inherent inertia. The early adjustment will have a certain impact on the later period. The existence of a lag period of the explanatory variables in the model will also cause the explanatory variables to be related to the disturbance term. Because the system generalized moment estimation (SYS-GMM) can effectively solve the endogenous problem of the model variables, this method is used in this paper for model robustness testing. The results show that the change trend of the main variables is consistent with the previous conclusions. The p value results of the Sargan test indicate that the original hypothesis of "all instrumental variables are valid" is accepted; the p values of AR (1) are all less than 0.1, indicating that "no first-order autocorrelation" is rejected at a significance level of 10%. The original hypothesis indicates that there is a first-order autocorrelation between the variables. The p values of AR (2) are all greater than 0.1, which means that the original hypothesis that "there is no second-order autocorrelation" is accepted. Sargan's test of the p value and the p values of AR (1) and AR (2) show that the selected instrument variables are reasonable, and the model identification is effective. The significance and sign of the main explanatory variables have not changed, and the direction of the mediation effect has not changed.

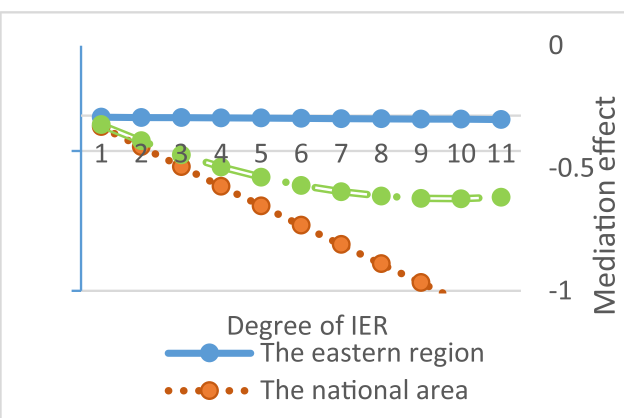

Fig. 8 Informal environmental regulation

Conclusions and policy implications

Conclusions

In this paper, environmental factors affected by environmental regulations are introduced into the production function, and the impact mechanism of environmental regulations and technological innovation on industrial structure upgrading is analyzed. Panel data of 30 provinces in China from 2005 to 2017 are used to investigate the relationship between heterogeneous environmental regulations, technological innovation, and industrial structure upgrading with the help of an intermediary model. The conclusions drawn by the research are as follows.

The influence of formal environmental regulations on technological innovation presents a u-shaped relationship, which would to some extent support the porter hypothesis. Formal environmental regulation has an inverted u-shaped relationship with industrial structure upgrading, which indicates that the excessive formal regulation is less likely to contribute industrial upgrading. Informal environmental regulation presents an inverted U-shaped relation to technological innovation and a U-shaped relation to industrial structure upgrading. Under formal and informal environmental regulations, the mediating effect of technological innovation is positive and negative respectively. With the increase of formal environmental regulations, the mediating effect in eastern China grows faster after passing the lowest point, which is higher than the mediating effect in central China. The coefficient of formal environmental regulation on technological innovation and industrial structure upgrading in western China is not significant. Although the effect of informal environmental regulation on industrial structure upgrading is u-shaped, its effect on technological innovation is not significant and the mediating effect of innovation in western China is not

Table 5 Regression results of mediating effect in western China

	Formal environmental regulation			Informal environmental regulation		
Variables	(1) IND	(2) R&D	(3) IND	(4) IND	(5) R&D	(6) IND
ER	0.0581 (0.0403)	− 0.140 (0.165)	0.0798* (0.0411)			
ER^2	− 0.00877 (0.00571)	0.000757 (0.0224)	− 0.00895 (0.00585)			
IER				− 0.115 (0.106)	0.477 (0.265)	− 0.0454 (0.109)
IER^2				0.111*** (0.0346)	− 0.139 (0.0924)	0.107*** (0.0302)
R&D			0.0528*** (0.0173)			− 0.0394** (0.0184)
FDI	− 8.475*** (2.641)	− 18.08 (11.25)	− 8.081*** (2.730)	− 1.614 (2.078)	− 5.646 (4.600)	− 5.549*** (1.947)
MDI	0.0561*** (0.0177)	0.352*** (0.0865)	0.0121 (0.0219)	0.00246 (0.0238)	0.0683 (0.0678)	0.0231 (0.0206)
URBAN	0.00350 (0.00271)	0.118*** (0.0121)	− 0.00323 (0.00267)	− 0.0230*** (0.00592)	0.157*** (0.0204)	− 0.0272*** (0.00362)
Constant	0.500*** (0.162)	1.888*** (0.733)	0.518*** (0.163)	1.641*** (0.294)	0.859 (1.013)	1.963*** (0.200)
Observations	104	104	104	104	104	104
Number of id	8	8	8	8	8	8

Standard errors in parentheses ***$p < 0.01$; **$p < 0.05$; *$p < 0.1$

established. The market index has a positive effect on industrial structure upgrading and innovation. It is shown that the higher the market index is, the more effective the market will be in resource allocation. The level of opening to the outside world has a negative effect on the upgrading of industrial structure and technological innovation. Urbanization rate has no significant impact on industrial structure upgrading, but it can promote technological innovation.

Policy implications

Properly enhancing the environmental regulation intensity can not only improve the technological innovation ability of enterprises but also promote the upgrading of industrial structure. At present, the degree of formal environmental regulation in most provinces and cities of China is still in the left side of the U curve of innovation and is in the left side of the

Table 6 Robustness test 1

	Formal environmental regulation			Informal environmental regulation		
Variables	(1) IND	(2) R&D	(3) IND	(4) IND	(5) R&D	(6) IND
ER	0.179*** (0.0279)	− 0.0605 (0.0444)	0.184*** (0.0276)			
ER^2	− 0.0213*** (0.00438)	0.0110 (0.00697)	− 0.0222*** (0.00434)			
IER				0.127*** (0.0388)	0.389*** (0.0556)	0.194*** (0.0407)
IER^2				0.0115*** (0.00320)	− 0.00445 (0.00458)	0.0100*** (0.00314)
R&D			0.0916*** (0.0319)			− 0.147*** (0.0332)
MDI	0.0677*** (0.0145)	− 0.0336 (0.0232)	0.0715*** (0.0144)	0.0731*** (0.0130)	− 0.0411** (0.0183)	0.0694*** (0.0127)
FDI	− 4.491*** (1.055)	− 8.543*** (1.684)	− 3.726*** (1.080)	− 2.016** (0.929)	− 2.857** (1.312)	− 2.499*** (0.913)
URBAN	0.0172*** (0.00218)	0.116*** (0.00348)	0.00636 (0.00431)	− 0.00900** (0.00386)	0.0775*** (0.00560)	0.00130 (0.00444)
Constant	− 0.306*** (0.152)	− 0.831*** (0.244)	− 0.317** (0.155)	0.624*** (0.155)	0.154 (0.242)	0.676*** (0.153)
Observations	390	390	390	390	390	390
Number of ID	30	30	30	30	30	30

Standard errors in parentheses ***$p < 0.01$; **$p < 0.05$; *$p < 0.1$

Table 7 Robustness test 2

	Formal environmental regulation			Informal environmental regulation		
VARIABLES	IND	R&D	IND	IND	R&D	IND
ER	0.0490*** (0.00301)	− 0.0303*** (0.00757)	0.0491*** (0.00263)			
ER^2	− 0.00491*** (0.000312)	0.00349*** (0.000889)	− 0.00500*** (0.000254)			
IER				0.0371*** (0.00694)	0.0703*** (0.0165)	0.0336*** (0.00735)
IER^2				0.00733*** (0.000991)	− 0.00888*** (0.00333)	0.00724*** (0.00101)
R&D			0.0652*** (0.00803)			− 0.0154*** (0.00471)
MDI	0.0185*** (0.00123)	− 0.0257*** (0.00407)	0.0205*** (0.00196)	0.0419*** (0.00201)	− 0.0431*** (0.00635)	0.0398*** (0.00288)
FDI	− 2.778*** (0.399)	− 4.844* (2.612)	− 1.887*** (0.490)	− 1.767*** (0.282)	− 5.587*** (1.950)	− 1.773*** (0.436)
URBAN	0.0121*** (0.000910)	0.0263*** (0.00344)	0.000697 (0.00121)	− 0.000243 (0.000528)	0.0320*** (0.00307)	− 0.00306*** (0.00107)
L.IND	0.765*** (0.00549)		0.763*** (0.00804)	0.652*** (0.00809)		0.664*** (0.00995)
L.R&D		0.764*** (0.0207)			0.754*** (0.0236)	
Constant	− 0.484*** (0.0525)	1.240*** (0.215)	− 0.527*** (0.0430)	− 0.0126 (0.0216)	1.240*** (0.132)	0.000152 (0.0462)
AR(1)	− 3.3839 (0.0007)	− 3.1243 (0.0018)	− 3.4688 (0.0005)	− 3.1135 (0.0018)	− 3.1382 (0.0017)	− 3.1673 (0.0015)
AR(2)	− 0.35333 (0.7238)	0.3413 (0.7329)	− 0.43407 (0.6642)	1.1243 (0.2609)	0.29811 (0.7656)	1.1148 (0.2649)
Sargan. (*p* value)	0.5099	0.4249	0.5780	0.4720	0.4351	0.5037

Sargan test results are over-recognized test values, AR (1) and AR (2) respectively represent the first-order and second-order difference residual sequences of the Arellano-Bond autocorrelation test

Standard errors in parentheses ***$p < 0.01$; **$p < 0.05$; *$p < 0.1$

inverted U curve of industrial structure upgrading. The degree of informal environmental regulation is on the left side of the U curve of industrial upgrading, and on the left side of the peak of technological innovation curve. At this time, the degree of informal environmental regulation is relatively weak. At present, there is no positive interaction between China's informal environmental regulation and technological innovation and industrial upgrading.

The final effect of technological innovation not only depends on the innovation itself, but also depends on a desired technology diffusion environment; the intermediate effect of technological innovation in the east and the middle of China is positive, but the intermediate effect value in the east is higher. The reason may be that the eastern region has a better innovation mechanism, a stronger diffusion capacity of technological innovation, and a higher efficiency of benign interaction among the three. Therefore, in order to maximize the final results of technological innovation, a guarantee system with reasonable structure and perfect functions should be established in an all-round way to achieve more efficient interaction among various innovation subjects, more sound technology transfer mechanism, and more effective diffusion of technological achievements.

The development tasks of each region should be formulated according to its actual developmental situations. The eastern region in China has a relatively good foundation and should give full play to its advantages to actively carry out "sophisticated" technological innovation and promote industrial upgrading. The central region is located in the connecting zone between the east and the west of China. Compared with the western region, the infrastructure construction is somewhat improved, but the mechanism of technological innovation diffusion is still slightly inadequate compared with the eastern region. It is necessary to establish a friendly environment for technological innovation diffusion. It includes feedback mechanism, fiscal and tax incentive mechanism, talent incentive mechanism, and resource integration mechanism to make the technology diffusion effect more obvious. Speeding up the construction of infrastructure and improving the infrastructure network are still the key points for the development of the western region. However, ecological environmental protection needs to be placed in an important position in the development of the western region so as to coordinate economic and social development with resources and environment.

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