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RESEARCH ARTICLE

Can environmental protection policies promote regional innovation efficiency: a difference-in-differences approach with continuous treatment

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Abstract
Environmental regulation and innovative development are essential means to solve the negative externalities of environmental pollution. However, developing countries often face the dual pressures of environmental pollution and innovative development. This paper focuses on whether environmental protection policies (*EPP*) can achieve a win–win situation between green development and innovative development. Based on the panel data of 277 cities in China from 2006 to 2016, this paper studies the impact of China's *EPP* on urban innovation efficiency by using a time-varying difference-in-differences approach. Combined with the geographical features of Chinese cities, we further take urban form into the mediating effect analysis. The results show that (1) *EPP* has a significant positive impact on innovation efficiency, and the result satisfies the parallel trend test; (2) the robustness test shows that *EPP* has technological innovation and diffusion effects; and (3) the mediating effect test show that urban form has a significant mediating effect on the impact of *EPP* on innovation efficiency. Therefore, environmental policies should be formulated considering the differences of urban form to achieve the optimal implementation effect.

Keywords Environmental protection policy (*EPP*) · Regional innovation efficiency · Difference-in-differences approach (DID) · Urban form · Mediating effect · Environmental regulations

Introduction

Technological innovation is a key driver for long-term green economic development. However, due to the externalities of the technology market and the financial market, environmentally friendly technological innovation activities lack market incentives and hard to meet the social needs. Policy intervention is therefore crucial. Rather than more generalized science and technology policies, environmental protection policies are more targeted at incentives for such technological innovation activities. Therefore, when evaluating the effects of environmental protection policies, in addition to their emission reduction effects and economic impacts, we should also pay attention to the technological innovation effects of these policies. The Porter hypothesis states that appropriate environmental regulations stimulate technological innovation (Porter 1991). Owing to externalities and path-dependent issues, technological innovation activities that contribute to the environment often lack market incentives, and environmental policies can provide a driving force for such technological innovation activities.

As the global largest trading country, China has primarily embedded downstream of global value chains (GVCs) based on its labor and fossil fuel factor endowments after its accession to the World Trade Organization (WTO) in 2001 (Antràs 2016). Crane and Mao (2015) showed that the cost of environmental pollution in China between 2000 and 2010 was close to 10% of the gross domestic product (GDP) per year. Long-term extensive development has led to high levels of embedding and pollution (a "double high"). Although China's economy has grown rapidly and already

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achieved remarkable results, yet its production process is characterized by high pollution and low environmental protection mainly in the first decades of twenty-first century. In 2011, the State Council of China promulgated the Strengthening Major Environmental Protection Policy (*EPP*), which requires an overall improvement in environmental regulations. At the same time, it also emphasizes the need to force technological innovation and transform the mode and path of economic development. However, it is unclear whether environmental protection policies, which are the main means of improving environmental regulation, will help improve China's innovation efficiency.

At present, most of China's cities are in the stage of rapid improvement in industrialization and urbanization. A large number of enclave-type urban industrial zones, university towns, and various urban new areas have driven the industrial and economic development. Especially after Covid-19, China's urban economic resilience has experienced some changes (Wang et al. 2022). Knowledge-intensive and creative enterprises and workers are particularly attracted to cities due to their social and economic diversity, urban environments, and high-quality amenities. As a result, cities can catalyze agglomeration dynamics that lead to learning, innovation, and productivity gains across industrial clusters (Chatman and Noland 2014). However, this overly decentralized and extensive urbanization expansion model reduces the efficiency of urban transportation and logistics and increases the cost of urban municipal construction. It also occupies a large amount of arable land and ecological land, which brings severe environmental pressure to the city and surrounding areas. Therefore, due to differences in urban form, the implementation effect of urban environmental policies and their impact on innovation will also vary.

In this study, we implemented *EPP* as a quasi-natural experiment to explore its impact on regional innovation efficiency. We aim to provide a reference for formulating a reasonable environmental regulatory intensity, promoting the improvement of technological innovation, and achieving energy conservation goals. There are two main novel contributions of this study. First, we introduced a difference-in-difference (DID) approach with a continuous treatment approach to analyze the impact of *EPP*. Existing studies commonly use general environmental policy indicators, such as Environmental Policy Stringency (Albrizio et al. 2017), to explore the relationship between environmental policy and innovation. We use a continuous measure of the intensity of treatment (i.e., ER), thereby capturing the casual effect of *EPP* on innovation. The exogeneity of this policy further ensures the accuracy of our results. Second, we analyze how *EPP* affects the efficiency of regional innovation on the basis of taking urban form as the intermediary variable. Cities are the main body where *EPP* plays its role. Recently, the development of regional innovation economy in China has induced the concept of innovation geography and innovation region, which has obvious geographical characteristics such as spatial agglomeration and spatial accessibility. There is little literature that considers mechanism analysis from the geographical characteristics of cities.

Literature review and theory development

Environmental policy and innovation

Nowadays, the relationship between environmental policy and innovation effect is a key issue in the academic field. This relationship will be different due to different economic and environmental backgrounds. The first concerns different economic environments, reflected in different countries, cities, industry types, etc. Cai et al. (2020) believe that for technology capital intensive industries, direct environmental regulation will actively and effectively promote green innovation, but for labor-intensive industries, this effect is not significant. Martínez-Zarzoso et al. (2009) used the number of patent applications to represent the extent to which enterprises' innovation decisions are affected by environmental regulations. They found that countries with well-functioning innovation systems are more vulnerable to environmental regulations. There is a counter-cyclical relationship between environment-related innovation and CO_2 emissions in BRICS countries. In terms of environment-related innovation and CO_2 emissions, the positive impact is greater than the negative impact (Manzoor and Zheng 2021; Ahmad et al. 2021). Qin et al. (2021) discussed the long-term correlation between the strength of environmental policies and green innovation based on the carbon neutrality goal. Yang et al. (2021) incorporated environmental regulation and green innovation into the unified measurement model, indicating that the Water Ecological Civilization City Policy (WECCP) can significantly improve the number of green patents in the pilot area, especially the overall level of green innovation in small cities, but not in large cities. Second, scholars analyzed the impact of different environmental policies on innovation. According to Noailly and Batrakova (2010), green technology patents are used to characterize the level of building technology innovation. Green technology patents here are related to building energy conservation. The classification of different environmental policy tools (energy standard, price, and energy R&D expenditure) and the influence mechanism of these policies on building energy conservation innovation in seven European countries were studied. The strength of regulatory standards has a significant impact on innovation capability, while energy prices have no significant impact. Environmental regulatory enforcement does not have an effective promotion effect on green technological innovation (Li et al. 2021). The focus of environmental policy implementation in the short term is to compare the marginal benefit of environmental protection with the marginal cost of pollution reduction (Jaffe et al. 2004). Specifically, the practical dynamic effects of environmental policy tools are often unsatisfactory, which may be due to the difference between the theoretical design and the practical effects of environmental policy; the implementation process is affected by a series of factors from policy makers, policy implementers, the public, and stakeholders (Hemmelskam 1997).

In addition, Lanoie et al. (2011) discussed the influence of environmental policies on enterprise performance and innovation; the change of the relative price of factors prompted enterprises to reduce the negative impact caused by environmental policies. Dechezlepretre et al. (2011, 2013) focused on OECD countries and analyzed the relative impact of their domestic and foreign policies on their technological innovation. It proves that foreign demand can better promote innovation growth. Löschel (2002) included technological progress in the analysis of economic effects of environmental policies from the perspective of enterprise, industry, and technological heterogeneity and believed that technological progress is an endogenous variable derived from demand and competition. Ren et al. (2021) used the two-stage least square method to deal with the potential selection bias, which appeared between environmental technology innovation and environmental management innovation. It was finally proved that environmental subsidies had a significant promoting effect on the former, but not on the latter, and there was no significant correlation between the two.

Hypothesis 1: Environmental policy has an impact on regional innovation, and the impact differs due to different economic and environmental backgrounds.

Environmental regulation and innovation

The classic environmental Kuznets curve (Grossman and Krueger 1991) shows that the relationship between economic innovation growth and environmental norms presents an inverted U-shaped curve. Specifically, in the initial stage of economic development and industrial development, the scale effect of environmental supervision will be greater than the technical structure effect, and the environmental level will decrease with economic growth. After entering the post-industrial era, the effects of technology and structure will exceed the scale effect. At this time, with economic growth, the environmental quality will continue to improve. Nie et al. (2021) analyzed panel data of China's coastal cities through supply chain management (SCM) and concluded that in China's less-developed coastal areas, marine environmental protection regulations play a significant role in promoting innovation growth, but this effect is not notable in relatively developed cities. Furthermore, environmental regulation not only impacts innovation like an "on" or "off" switch, but it also acts as a steering wheel that adjusts the direction of innovation (Kemp et al. 2000). Pickman (1998) suggested that environmental regulations promote the flow of enterprise innovation resources to the environment; the overall innovation input does not decrease, but other types of innovation are replaced owing to such flow, resulting in a change in innovation direction. Lv et al. (2021) found that environmental regulation can play a regulatory role in finance and innovation. The stronger the environmental regulations, the innovation efficiency of green technology is improved.

The existing literature is mainly focused on the types of environmental regulations, and the heterogenous effect in different industries and regions. One is the impact of different types of environmental regulations on innovation. Jiang et al. (2021) found that in contrast to industrial environmental regulation, regional environmental regulation is conducive to the improvement of enterprise innovation performance. Compared with enterprise environmental information disclosure (EID), environmental management system certification (EMSC) has a better incentive effect on enterprise innovation owing to the higher cost of EMSC and stronger innovation motivation of enterprise environmental technology (Jiang et al. 2020). Market-based environmental regulation helps promote technological innovation, while control-based environmental regulation has no significant impact on innovation (Pan et al. 2019). Financial incentives have a good guiding effect on innovation (Hille et al. 2020). As a type of market-based environmental regulation, carbon emission trading systems are expected to promote emission reduction targets, while their impact on the innovation ability of enterprises is also attracting attention. Therefore, a lack of sufficient funds to invest in innovative research and development significantly reduces enterprises' innovation capacity (Shi et al. 2018). Peng et al. (2021) used the DID method to analyze the regulatory effect of an SO_2 emission trading pilot (ETP) and tested Porter's hypothesis. The results showed that in the implementation of SO_2 ETP, the more conducive is market-based environmental regulation to the increase of the "innovation effect" in enterprises, which is greater than the "compliance cost." The focus of sustainable environmental policy is a combination of market-based environmental regulation and control-based environmental regulation (Liu et al. 2020).

Second, the impact of environmental regulations on innovation varies in different industries. Adam and Jaffe (1996) characterized the intensity of environmental regulation by the expenditure directly caused by environmental regulations and found that the relationship between environmental regulation expenditure and enterprise patent activities is not significant. However, even if the impact is weak, after a specific industry is controlled, there is a positive correlation between cost tracking and enterprise innovation input. Chakrabort and Chatterjee (2017) conducted a quasi-natural experiment in the chemical industry and found that upstream enterprises' innovation activities produce a "substitution effect" and reduce downstream enterprises' innovation investment. Ai et al. (2021) used DID to test 6631 chemical enterprises and found that the top 1000 Energy Consuming Enterprises Plan (T1000P) had a negative impact on technological innovation. Rennings and Rammer (2011) analyzed the enterprise data of the German technological innovation industry and believed that an increase in environmental innovation would not reduce the overall innovation capacity of enterprises; the results of environmental innovation were better than those of other innovation directions. When focusing on specific industries, the two have opposite effects. For example, those who insist on innovation in the transportation industry also need to pay compliance costs, which greatly reduces their competitiveness. However, in industries such as waste utilization, such costs are often transferred to customers or offset, and innovation compensation can play a major role.

Third, the impact of environmental regulations on innovation varies in different regions. Cao et al. (2020) showed that the Yangtze River Delta Economic Belt has a high-quality operation mode in terms of economic growth, environmental regulation, and innovation capacity and that the relationship between economic growth and environmental regulation presents an inverted U-shape. Based on China's provincial regional data and spatial Dubin model, Dong et al. (2020a) tested the chain reaction of environmental regulation to local and adjacent areas and found that there was a significant chain reaction of environmental regulation in geographically and industrially adjacent areas, but not in economically adjacent areas. In addition, environmental regulations promote investment in polluting industries in surrounding areas, and the overall green technology innovation is not strong enough and presents a U-shaped change.

The mechanism of how environmental regulation affects innovation

Scholars have conducted extensive research on the mechanism by which environmental regulation affects innovation. Ren and Ji (2021), based on panel data of 11 provinces and cities in coastal areas of China, verified that environmental regulations show different effect stages under different technological innovation levels using the threshold effect model. In the low-level innovation stage, the "compliance cost" of environmental regulations is greater than the "innovation compensation"; the profit space of enterprises is compressed by the cost of environmental regulations, and enterprises cannot continue to invest in technological innovation. Once the high-level innovation stage is entered, the path for enterprises to benefit from technological innovation achievements can be constructed, and "innovation compensation" will play a major role. Enterprises will be more willing to invest in technological progress and innovation to achieve a virtuous cycle. Fan et al. (2021) further studied the spillover effect of environmental regulations on China's urban environment by calculating the efficiency of green innovation, establishing a spatial econometric model, and conducting a spatial autocorrelation test; the results showed that the intensity of environmental regulations and the efficiency of green innovation showed a positive U-shaped relationship. There is heterogeneity in the Porter effects in different countries. In developing countries, the Porter effect is not common, but corruption is the key factor determining this effect. Taking China as an example, in regions where enterprises spend a lot on bribery and have a high degree of corruption, environmental regulation has a significant positive impact on enterprise innovation (Fu and Jian 2021). At the same time, De Santis et al. (2021) verified the strong Porter hypothesis based on the environmental policies of 18 OECD countries and used hourly data to represent productivity, proving that the environmental regulation policies of OECD countries have a positive effect on productivity, especially in developed countries with information and communication technology. Countries can make better use of innovation opportunities provided by environmental policies to indirectly improve productivity and economic growth by promoting capital accumulation.

Environmental regulations, urban form, and innovation

The overall physical composition of a city is called urban form, specifically, the physical environment of the city and the spatial structure and structure of various activities (Anderson et al. 1996). Urban form is composed of two parts: tangible form and intangible form (Ewing 1997). In detail, urban form is the external spatial manifestation of the endogenous elements of urban development, and the reflection of the city's internal political, economic, social structure, and cultural traditions in urban settlements, urban plane form, internal organization, architecture, and the layout of building groups. Hamidi and Zandiatashbar (2019) found that urban compactness is positively associated with regional innovation capacity. Abramovsky and Simpson (2011) explored the role of geographic proximity in firm-university innovation linkages for Great Britain. The results showed that firms located near research institution tended to cooperate with universities.

> Hypothesis 2: Urban form exerts an intermediating effect in the impact of environmental policy on regional innovation.

Background, data, and model

Background

From the early days of the founding of the People's Republic of China to the reform and opening up, and now, China's economy has achieved rapid development; alongside, unprecedented progress has been made in ecological and environmental protection. In particular, China's national environmental strategy and policies have undergone tremendous changes, evolving from "three wastes" governance to the governance of river basin areas. China's environmental protection policy has shifted from the implementation of total pollutant control to the improvement of environmental quality. At present, China has established an environmental strategic policy system that adapts to ecological civilization; "Beautiful China," China's national environmental protection policy, is generally released before or after the National Environmental Protection Conference (NEPC). The NEPC, chaired by the State Council, aims to make a series of major decisions to address China's environmental problems. To date, the NEPC has held eight sessions. The main contents of the past NEPCs and their enactment policies are shown in Table 1.

The rapid growth of China's economy is inseparable from the support of industry. Due to the rapid development of heavy industry, China's ecological environment is facing an increasing threat of pollution. In 2011, the State Council of China issued the Strengthening Major Environmental Protection Policy. This was the first time that total pollutant control was raised to the height of the national environmental protection strategy. It emphasized innovation especially in environmental protection industries. Environmental protection planning has transformed from soft to hard constraints. At the same time, this was also the first time that the State Council had put forward opinions on the major work of environmental protection. Since the release of the *EPP*, China's environmental protection investment has increased significantly and is equivalent to the total investment in environmental protection in the past 20 years. During this period, the sewage treatment rate of cities in the country increased from 52% in 2005 to 72% in 2012. The harmless treatment rate of municipal solid waste rose from 52 to 78%. The proportion of thermal power desulfurization installed capacity increased from 12 to 82.6%. More than a decade has passed since the implementation of the *EPP*, and its policy effects are visible. Therefore, we selected data after the 6th NEPC and before the 8th NEPC for analysis. Owing to data limitations, the sample selected for this study were from 2006 to 2016.

Table 1 China's National Environmental Protection Conference (NEPC)

Year	Conference	Main content	Policy
1973	The 1st National Environmental Protection Conference	Preliminary treatment of some seriously polluting industrial enterprises, cities, and rivers has been carried out	"Provisions on the Protection and Improvement of the Environment"
1983	The 2nd National Environmental Protection Conference	Environmental protection has been established as a basic national policy	"Decisions on Environmental Protection"
1989	The 3rd National Environmental Protection Conference	Five new environmental protection systems and measures were proposed	"Environmental Protection Goals and Tasks for 1989–1992"
1996	The 4th National Environmental Protection Conference	The policy of attaching equal importance to pollution prevention and ecological protection has been determined	"Decisions on Several Issues Concerning the Strengthening of Environmental Protection"
2002	The 5th National Environmental Protection Conference	Environmental protection was proposed to be an important function of the government and an important part of sustainable development	"National Environmental Protection 'Tenth Five-Year Plan'"
2006	The 6th National Environmental Protection Conference	The direction of promoting comprehensive and coordinated sustainable economic and social development was proposed	"National Environmental Protection 'Eleventh Five-Year Plan'"
2011	The 7th National Environmental Protection Conference	It was proposed to promote economic transformation and improve the quality of life	"The Strengthening Major Environmental Protection Policy"
2018	The 8th National Environmental and Ecological Protection Conference	It was proposed to increase efforts to promote the construction of ecological civilization and solve ecological and environmental problems	"Opinions on Comprehensively Strengthening Ecological Environmental Protection and Resolutely Fighting the Tough Battle of Pollution Prevention and Control"

Regression model

To solve the bidirectional causality problem is the key of econometric model, especially in environmental economics literatures (Fan et al. 2020; Fan and Zhang 2021). For cities, the implementation of *EPP* has a certain exogeneity. This is because China's environmental policy is formulated by the State Council and the State Environmental Protection Administration of China. The prefecture-level municipal governments can hardly exert an influence on the policy-making process. Hence, we take the implement of *EPP* as an ideal "quasi-natural experiment." Therefore, the DID model based on quasi-natural experiments can alleviate endogenous problems to a large extent. Spatial DID methods based on spatial weight matrices are commonly used in city-level empirical studies. However, some scholars have started to focus on the endogeneity of the spatial weight matrix, which assumes that the spatial weight matrix is not exogenous given. They assume that the spatial weight matrix includes an unknown nonparametric function to be estimated by the model (Kelejian and Piras, 2014). Qu and Lee (2015) point out that the exogeneity of the spatial weight matrix is a key to ensure the accuracy of empirical results. If the spatial weight matrix is endogenous, then the empirical results will be biased. Therefore, referring to Qian (2008), the regression model is constructed by the DID method with continuous treatment in this paper as shown in Eq. (1):

$$IE_{it} = \beta_0 + \beta_1 EPP_{it} + \gamma X_{it} + \Phi_{it} + \mu_i + \varepsilon_{it} \tag{1}$$

where subscript i denotes city and t denotes year; IE_{it} is the dependent variable, which denotes the innovation efficiency of city i in year t. $EPP_{it} = ER_{it} \times \mathrm{After}_{it}$, and it is the DID variable with a continuous treatment. ER_{it} denotes the indicator of environmental regulation of city i in year t. After_{it} is the dummy variable denoting whether city i is treated in year t. *EPP* came into effect in 2011, so when $t < 2011$, After_{it} is 0; otherwise it is 1. β_1 is the estimated coefficient that represents the impact of *EPP* on regional innovation. X_{it} is the set of control variables. ε_{it} is the random disturbance term in the model. Φ_{it} and μ_i represent the year fixed effect and city fixed effect, respectively.

Data sources and description

The data in this paper come from city-level databases of China, including China Urban Statistical Yearbook, China Regional Economic Statistical Yearbook, and China Statistical Yearbook. After merging, the final sample used in this paper is panel data of 277 cities in China from 2006 to 2016. Control variables are as follows.

(1) GDP per capita (*G*): Howells (2005) pointed out that there was a positive and significant impact of innovation on economy. González-Serrano et al. (2019) studied in the sports industry the relationship between innovation performance and GDP per capita. Evidence from EU countries showed a significant positive relationship between the two. Therefore, we use it as a control variable in regression analysis.

(2) Openness (*O*): In developing countries, although trade openness may lead to the dilemma of "low-end lock-in" in the domestic manufacturing industry due to intensified import competition, it can also significantly promote innovation (Belazreg and Mtar et al. 2020). Dotta and Munyo (2019) provided an assessment of policies that promote trade openness. According to the results, the policy has a clear role in promoting the improvement of a country's innovation ability. Specifically, we measure openness by the ratio of total import and export to GDP.

(3) Transportation (*TR*): Improvements in transportation facilities tend to be positively correlated with regional innovation (Tang et al. 2022). Agrawal et al. (2017) found that the traffic facilities in the region will improve the innovation effect by affecting the flow of knowledge and information. In this paper, we introduce the urban road area to examine the effect of transportation in the regression model.

(4) Telecommunications (*TE*): Evidence from China and Pakistan showed that the telecommunication industry is an important guarantee for economic development and policy implementation. The improvement of industrial modernization and innovation capability is inseparable from the support of the telecommunication industry (Fei and Rasiah 2014; Owoeye et al. 2020). Therefore, we use the total amount of telecom business to measure telecom.

(5) Energy intensity (*EI*): An increase of innovation activities often occurs simultaneously with the improvement of energy consumption and energy efficiency (Chakraborty and Mazzanti 2020), but this situation is not uniform across countries. We include energy intensity as a control variable in the baseline regression.

(6) Human capital (*H*): Current studies found heterogenous effect of human capital on innovation, as it is positive in developed regions (Ireland) but not significant in poor countries (sub-Saharan Africa) (Danquah and Amankwah-Amoah 2017; Lenihan et al. 2019). We use the number of university students to measure human capital in the baseline regression.

(7) Financial development (*F*): Schumpeterian models of finance, entrepreneurship, and economic growth shows that higher levels of financial development coincide with stronger innovative activity (Meierrieks 2014). Hsu et al. (2014) also found that the development of equity markets and credit markets can encourage innovation activities. We calculate financial development

by the ratio of the balance of deposits and loans of all financial institutions to the city's GDP.

(8) Industry structure (*IS*): The transformation of industrial structure is an important way for developing countries to accelerate economic development. Hunt (2004) built a model of sequential innovation with endogenous industry structure and found that the more stringent the patentability standard, the more firms tend to innovate. According to Gan et al. (2011), we use deviational range of industrial structure to measure industrial structure.

To reduce the degree of sample heteroscedasticity and the fluctuation of variables, we take the natural logarithm of each variable in the regression. The variable descriptions are shown in Table 2. During the data merging process, we excluded samples missing key variables. Descriptive statistics are summarized in Table 3.

Innovation efficiency

The measurement of efficiency measurement in the existing literature can be mainly divided into two categories. The first is the parametric method represented by the stochastic frontier production function analysis (SFA). SFA is a method for estimating efficiency parameters based on stochastic frontier production function. This method first assumes that the production function is equal to the random error distribution (Aigner et al. 1977; Meeusen and Broeck 1977; Battese and Corra 1977). The second is the non-parametric method represented by data envelopment analysis (DEA), which requires neither the setting of the production function nor the estimated parameters, and thus is more convenient to use. Compared with the advantages of DEA, SFA requires the estimation of input–output production model and is easily affected by the dimension of index data. However, the disadvantage of DEA is that it is easy to ignore the relaxation factors and unexpected output factors and then overestimate the efficiency level. The decision-making unit with efficiency value of 1 cannot be deeply studied. To modify this model, Tone proposed SBM model in 2001 and then proposed super SBM model in 2002. The super SBM model distinguishes and sorts all decision-making units whose efficiency value is greater than 1 and also takes into account the relaxation variables. Based on Tone (2002), this paper draws on the efficiency estimation method of Fan et al. (2021) and Tang et al. (2022), and slack factor and undesired output are added on the basis of traditional DEA. The innovation efficiency is measured by constructing the SBM-based Super SBM-DEA model. The following is the specific equation model:

$$\rho^{*} = \min\rho = \min\frac{1-\left(\frac{1}{N}\sum_{n-1}^{N}\frac{S_n^x}{x_n^k}\right)}{1+\left[\frac{1}{M+I}\left(\sum_m^M\frac{s_m^y}{y_m^k}\right)+\sum_{i+1}^{I}b_i^{k'}\right]}$$

$$\text{constraint condition}\begin{cases}\sum_{k=1}^{K} Z_k^y y_m^k s_m^y y_m^{k'} \\ \sum_{k=1}^{K^v} Z_k^b b_i^k + s_i^b = b_i^{k'}, i = 1, \cdots, I \\ \sum_{k=1}^{K} Z_k^x x_n^k + s_n^x = x_n^{k'}, n = 1, \cdots, N \\ Z_k^i s_m^y s_i^b s_n^x \end{cases} \quad (2)$$

Table 3 Descriptive statistics

Variables	(1) *N*	(2) Mean	(3) Std	(4) Min	(5) Max
IE	3047	0.416	0.216	0.107	1
EPP	3047	0.580	0.186	0	0.945
G	3047	50,666	317,474	2,767	1.444e+07
O	3047	72,112	179,631	4.500	3.083e+06
TR	3047	8864	8754	346	95,009
TE	3047	426,192	796,985	11,989	1.469e+07
EI	3047	196.8	298.1	2.037	2580
H	2865	76,040	137,304	231	1.057e+06
F	2970	2.054	0.979	0.560	8.777
IS	2970	0.272	0.216	0.000243	3.430

Table 2 Variable descriptions

Variable types	Name	Descriptions	Sources
Dependent variable	*IE*	Innovation efficiency	China City Statistical Yearbook; China Statistical Yearbook
DID variable	*EPP*	Environmental protection policy	China City Statistical Yearbook; China Regional Economic Statistical Yearbook
Control variables × *q*	*G*	GDP per capita	China City Statistical Yearbook
	O	Openness of international trade	
	TR	Urban road area	
	TE	Total amount of telecom business	
	EI	Energy Intensity	
	H	Human capital	
	F	Financial development	
	IS	Industry structure	

where ρ is the calculated efficiency. The slack factors are s_m^y, s_i^b, and s_n^x. y_m^k, b_i^k, and x_n^k are the input and output values of the k' production unit in period t'. The weight of input and output variables are determined by Z_k^y and Z_k^x. When there is an efficiency loss in the production unit, it can be improved by optimizing the input quantity N, the desired output M, and the undesired output I. The input variables most directly related to innovation activities are R&D capital and talents. The desired output M includes academic outputs, patents, and new products sales. The undesired output I includes industrial wastewater discharge, industrial SO_2 discharge, and industrial coal consumption.

In addition, we choose government support, informatization level, marketization level, and local financial science and technology expenditure to measure innovation environment variables. The measurement of the variables is shown in Table 4.

In the robustness test, we measure the innovation ability through the number of patents granted. In this study, total factor productivity (TFP) is used as the proxy variable of technological innovation factors, and the number of scientific research practitioners is used as the proxy variable of diffusion effect in the regression. Among them, the number of scientific research practitioners can effectively reflect the level of human capital, and TFP is often regarded as an indicator of scientific and technological progress. We downloaded and sorted out the number of scientific research practitioners from 2006 to 2016 from China Urban Statistical Yearbook and China Statistical Yearbook and collected the grant of patents at the urban level from China's national intellectual property database.

Environmental regulation

There are three methods to measure the level of environmental regulation. First, a single indicator is used to measure the intensity of environmental regulation, including environmental regulatory policies, environmental governance inputs, and environmental policy performance indicators (Aiken et al. 2009). In addition, some scholars use indirect indicators, such as per capita income, to measure the intensity of environmental regulation (Cole et al. 2008). Second, pollution emissions are used to construct comprehensive indicators. For example, five individual indicators, such as the sulfur dioxide removal rate and industrial soot removal rate, were selected to calculate the comprehensive index to reflect the intensity of regional environmental regulations. Third, assign a score to the strictness of environmental regulations according to certain rules. For example, van Beers and van den Bergh (1997) set up a quantitative system with a total score of 24 points by constructing an environmental regulation intensity system to measure the intensity of national environmental regulations.

In summary, the single indicator method may lead to bias in the research conclusion, because it is only measured from a certain aspect of environmental regulation. The assignment scoring method is difficult to avoid the interference of human subjective factors, while the search limitations of urban data make it impossible to examine the intensity of environmental regulations from different perspectives. Based on this, the level of environmental supervision is measured by comprehensive index method in this study, which included five individual indicators: industrial smoke (powder) dust

Table 4 Descriptive statistics of input, output, and environment variables

Variable types	Name	Measurement
Input variables	R&D capital	Basic research, applied research, and experimental research expenditure
	R&D talents	Basic research, applied research, and experimental practitioners
Output variables	Academic outputs	The number of SCI and EI published paper The number of scientific and technical monographs
	Patents	The number of patent applications The number of patents granted
	New product sales	New product sales revenue
	Industrial wastewater discharge	Industrial wastewater discharge per GDP
	Industrial SO_2 discharge	Industrial SO_2 discharge per GDP
	Industrial coal consumption	Industrial coal consumption per GDP
Environment variables	Government support	The proportion of government funds in the fund-raising of regional science and technology funds
	Informatization level	The number of telecommunications per capita
	Marketization level	Marketization index
	Local financial science and technology expenditure	The expenditure by the local government and related departments to support scientific and technological activities

removal rate, industrial SO_2 removal rate, comprehensive utilization rate of general industrial solid waste, harmless treatment rate of domestic waste, and centralized treatment rate of sewage treatment plants. The calculation steps were as follows: first, all the indicators were standardized; second, the entropy value method was used to determine the index weights, and the environmental regulation composite index was calculated according to the weights and standardized values. The higher the composite index score, the stricter the government's regulation of the environment.

Urban form

Since the late 1970s, China has entered a process of rapid urbanization, which has involved a series of enormous restructuring of economic and social structures. The development of cities and economy is changing the basic natural form and structure of Chinese cities. China's urban form has undergone substantial changes due to changes in transportation and housing due to development needs. The core of urban form is the rational organization and layout of various functions in the city. That is, under the condition of minimizing the occupation and interference of natural resources and environment, improve the urban space utilization efficiency and logistics efficiency, to strengthen the implementation effect of various policies. The space utilization efficiency index is measured by population, employment, economy, and land use data. The logistics efficiency index considers the circulation efficiency of people and logistics in the city. Efficient logistics efficiency can reduce commuting costs, transportation energy consumption, and the infrastructure network cost. Therefore, urban form not only reflects the differences in urban spatial form and geographical characteristics, but also changes the effect of urban policy implementation. We chose fractal dimension (*FD*) to measure space utilization efficiency and largest patch index (*LPI*) and patch density (*PD*) to measure logistics efficiency. The data comes from the China Urban Statistical Yearbook and the China Urban Construction Statistical Yearbook. Furthermore, we used ArcGIS 10.2 to complete the urban land map and calculated the urban land area of each city. We used the R data package SDM Tools to calculate the urban form indexes.

First, urban spatial form has self-similarity, and *FD* is used to quantify the self-similar characteristics of urban spatial form. There are mainly two methods for measuring the *FD* of the surface shape: the small box counting method and the formula calculation method. In this paper, the formula calculation method is used to measure *FD* of urban land shape in each city, namely, $\mathrm{FD} = \ln a / 2\ln(0.25p)$, where a denotes the total area and p denotes the side length of urban land. *FD* is an indicator of the complexity of urban form. In the early stage of urban development, the urban structure still needs to be improved. When the city develops to the later stage, *FD* will tend to be stable (Chen 2011).

Second, the element characteristics of urban agglomerations constitute the basis for the scale efficiency of urban form (Pham et al. 2011). *LPI* is currently the mainstream method to measure the element characteristics of urban form. *LPI* is measured by the proportion of the largest urban land patch, that is, the proportion of the largest urban land patch in the total urban land area. The calculation formula is as follows: $\mathrm{LPI} = \max a_i / a$, where a_i denotes the area of the largest urban land patch i, and a denotes the total area. *LPI* is the central agglomeration degree of urban land. A higher *LPI* value indicates that urban development is mainly concentrated in a continuous area, and its urban form is more compact (Zelenyuk 2015).

Third, we use *PD* to measure the structural characteristics of urban agglomerations. *PD* represents the average land area corresponding to each land patch within the city's administrative area. *PD* is often used in landscape ecology research. Patch is the basic unit of landscape pattern, which refers to the non-linear area with similar characteristics that is different from the surrounding background. The higher the *PD*, the greater the fragmentation of urban land is, and the lower the urban traffic efficiency and the use efficiency of municipal facilities. The calculation formula of *PD* is as follows: $\mathrm{PD} = i/a$, where i denotes the number of urban patches, and a denotes the total area. An increase in *PD* suggests that new development is more dispersed, leading to higher fragmentation and a higher risk of urban sprawl (Schneider and Woodcock 2008).

Results

Parallel trend test

DID is an effective tool for policy effect evaluation. This paper will analyze the promotion effect of ER on innovation efficiency through double difference model. The principle is to observe the changes of dependent variables in the case of whether the policy occurs or not under the theoretical framework of counterfactual. The premise of using DID method is that the two groups of samples (control group and experimental group) must have the same development trend. If the development trend is different, it means that other factors affect the changes of the explained variables. In other words, parallel trend test is the basic premise of empirical research. Therefore, following Alder et al. (2016), we test the parallel trend hypothesis by adding the interaction terms of the time dummy variables with the treatment group before and after the opening of the *EPP*, respectively. The dynamic evolution of the effect of *EPP* on innovation efficiency is also analyzed. The regression model is as follows:

$$IE_{it} = \beta_0 + \beta_1 EPP2009_{it} + \beta_2 EPP2010_{it} + \beta_3 EPP2012_{it} + \beta_4 EPP2013_{it} + \gamma X_{it} + \Phi_t + \mu_i + \varepsilon_{it} \quad (3)$$

The results are shown in Table 5. The interaction term coefficients of the year dummy in 2009 and 2010 are not significant. The interaction term coefficients of the year dummy in both 2012 and 2013 are significant at the 1% level. Hence, the regression results satisfy the assumption of parallel trends, while *EPP* has a significant and long-term positive effect on innovation efficiency over time.

Baseline regression

We conduct the baseline regression by using a panel fixed effects model, and the results are shown in Table 6. We include both year fixed effects and city fixed effects in the regression. Among them, the year fixed effects exclude the influencing factors that change over time, while the city fixed effects control for the heterogeneity of cities. Without including any control variables in column (1) of Table 6, the results show that the coefficient is positive and significant at the 1% level, which indicates that *EPP* significantly improves innovation efficiency. The quantity of innovation efficiency between cities increased by 9.5% after the implementation of the *EPP*. These results are consistent with those of Dong et al. (2020b). From the perspective of environmental externalities, technological innovation needs more policy support to reach the optimal level for society.

Table 5 Parallel trend test

Variables	(1)	(2)	(3)	(4)
*EPP*2009	−0.014			
	(0.012)			
*EPP*2010		−0.020		
		(0.022)		
*EPP*2012			0.089***	
			(0.009)	
*EPP*2013				0.071***
				(0.009)
Ln*G*	−0.003	0.018**	0.033***	0.025***
	(0.007)	(0.008)	(0.007)	(0.007)
Ln*O*	0.014**	0.024***	0.025***	0.019***
	(0.006)	(0.006)	(0.006)	(0.006)
Ln*TR*	0.022***	0.010	0.004	0.006
	(0.008)	(0.008)	(0.008)	(0.008)
Ln*TE*	0.009***	0.011***	0.012***	0.011***
	(0.003)	(0.003)	(0.003)	(0.003)
Ln*EI*	0.001	0.006	0.011*	0.010*
	(0.006)	(0.006)	(0.006)	(0.006)
Ln*H*	0.003***	0.004***	0.004***	0.004***
	(0.001)	(0.001)	(0.001)	(0.001)
Ln*F*	0.043***	0.031***	0.021***	0.020***
	(0.006)	(0.006)	(0.006)	(0.006)
Ln*IS*	0.053**	0.045**	0.036*	0.037*
	(0.022)	(0.022)	(0.022)	(0.022)
Constant	0.443***	0.882***	1.152***	1.003***
	(0.091)	(0.094)	(0.085)	(0.080)
Observations	3,047	3,047	3,047	3,047
Year FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes

(1) Robust standard error in parentheses; (2) ***, **, and * indicate 1%, 5%, and 10% significance levels, respectively

Promoting innovation depends on two policies: environmental policy, which corrects environmental externalities, and technology policies to correct failures in the technology market. Effective environmental policies will put pressure on companies to reduce emissions, forming a shadow price for emissions and helping to induce technological innovation. This is a necessary form of government intervention. Regarding the coefficient of the control variables, GDP can significantly contribute to innovation efficiency. This is consistent with the findings of Howells (2005). During the sample period, China's economy developed rapidly, and the long-term accumulation of capital promoted China's innovation efficiency. Transportation has a significant and positive correlation with innovation efficiency. As a major locus for infrastructure construction, the rapid development of China's transportation facilities, especially the construction of highways, has garnered global attention. The improvement of transportation facilities has further promoted the cross-regional flow of innovative elements.

Overall, rising energy intensity can promote innovation efficiency. Column (7) shows that higher openness favors technology transfer and reduces pollution emissions. Similarly, the existing literature reveals that developing economies represented by China should expand the scale of trade opening up and benefit from the advanced technology of other developed countries. Managing trade flows and designing comprehensive technical, trade, and environmental policies can achieve sustainable economic development. In addition, the development of China's telecommunications industry has also promoted the improvement of regional innovation efficiency. Human capital, as an important element in strengthening the ability of enterprises to absorb and develop new knowledge, is an important part of cutting-edge innovation and catching up with innovation. Financial development and industrial structure are also positively correlated with regional innovation efficiency.

Robustness test

Robustness test based on different measurements of innovation

In existing literatures, patents are commonly used to measure the innovation ability of an enterprise or a region. Therefore,

Table 6 Baseline regression

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
EPP	0.014**	0.070***	0.085***	0.085***	0.084***	0.089***	0.091***	0.101***	0.091***	0.090***
	(0.006)	(0.009)	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)
Ln*G*		0.054***	0.046***	0.046***	0.046***	0.039***	0.036***	0.034***	0.034***	0.034***
		(0.007)	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
Ln*O*			0.029***	0.029***	0.029***	0.028***	0.026***	0.027***	0.029***	0.029***
			(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)
Ln*TR*					0.001	0.004	0.005	0.003	0.001	0.002
					(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
Ln*TE*						0.016***	0.015***	0.014***	0.013***	0.013***
						(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Ln*EI*							0.011*	0.006	0.008	0.008
							(0.006)	(0.006)	(0.006)	(0.006)
Ln*H*								0.004***	0.004***	0.004***
								(0.001)	(0.001)	(0.001)
Ln*F*									0.026***	0.026***
									(0.006)	(0.006)
Ln*IS*										0.037*
										(0.022)
Constant	0.406***	0.947***	1.102***	1.102***	1.101***	1.148***	1.240***	1.180***	1.174***	1.169***
	(0.003)	(0.067)	(0.073)	(0.073)	(0.074)	(0.074)	(0.088)	(0.090)	(0.090)	(0.090)
Observations	3047	3047	3047	3047	3047	3047	3047	3047	3047	3047
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

(1) Robust standard error in parentheses; (2) ***, **, and * indicate 1%, 5%, and 10% significance levels, respectively

we first use the number of patents granted to measure innovation. The results in Table 7 show that there is a significant positive relationship between *EPP* and the number of patents granted. Second, we use TFP as a dependent variable into the regression. The results show that *EPP* also promotes TFP. Finally, we use the number of scientific research practitioners to measure innovation, and there is still a positive relationship between the two.

This reflects the technological innovation and diffusion effects of environmental policies. Foreign technology generally diffuses domestically through two channels: One is directly adopted by domestic manufacturers, and the other is to affect the productivity of domestic research and development. For the former, existing patents from foreign countries are rapidly being used domestically. For the latter, foreign technology generally needs to be localized through domestic research and development, which can be observed by the international citation of patents (Popp 2010). Recent studies have used patent data to classify technological innovation in detail, and most empirical studies have found that national environmental policies play a positive role in promoting green technology innovation. In a study using pollution abatement expenditure (PACE) as a policy proxy variable, Brunnermeier and Cohen (2003) found that the impact of PACE on environmental innovation in US manufacturing firms was significantly positive, but the impact of government monitoring and enforcement was not significant. In addition, observational data and survey data reached similar conclusions. Johnstone et al. (2012) surveyed data using patent and firm perceptions of environmental policy strength and found that environmental regulation has a positive inducement effect on clean-tech innovation.

Robustness test based on different regression methods

We introduce the ordinary least squares (OLS) method, bilateral truncation 1%, bilateral winsorization 1%, and the high-dimensional fixed effect model in this robustness test. The OLS method is carried on the cross-sectional data to test the accuracy of the baseline regression results. Considering that the ER of the city-level extremum may affect the regression results on both ends of the sample, the original samples were subjected to bilateral truncation at the 1% level. The 1% samples with the highest ER value and the 1% samples with the lowest ER values were eliminated before the baseline regression was conducted. Similar to the idea of bilateral truncation, to exclude the influence of outliers on the regression results, this study processed the basic

Table 7 Robustness test based on different measurements of innovation

Variables	(1) Patents	(2)	(3) TFP	(4)	(5) Scientific research practitioners	(6)
EPP	2.411***	1.167***	0.049***	0.004	3.550***	1.522***
	(0.031)	(0.045)	(0.005)	(0.010)	(0.143)	(0.239)
Ln*G*		−0.612***		−0.031***		−0.931***
		(0.032)		(0.007)		(0.172)
Ln*O*		−0.195***		−0.001		0.485***
		(0.025)		(0.005)		(0.133)
Ln*TR*		0.254***		0.001		0.571***
		(0.034)		(0.007)		(0.180)
Ln*TE*		−0.040***		0.001		0.368***
		(0.012)		(0.003)		(0.066)
Ln*EI*		−0.143***		−0.009*		−0.504***
		(0.026)		(0.006)		(0.138)
Ln*H*		0.009**		0.001		0.024
		(0.004)		(0.001)		(0.020)
Ln*F*		0.317***		0.018***		1.950***
		(0.026)		(0.006)		(0.138)
Ln*IS*		0.098		0.026		−0.664
		(0.094)		(0.020)		(0.502)
Constant	5.825***	−5.618***	−0.069***	−0.543***	−1.171***	−15.074***
	(0.015)	(0.391)	(0.003)	(0.083)	(0.071)	(2.082)
Observations	3047	3047	3047	3047	3047	3047
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes

(1) Robust standard error in parentheses; (2) ***, **, and * indicate 1%, 5%, and 10% significance levels, respectively

samples by bilateral winsorization (Crinò and Ogliar 2015). The high-dimensional fixed-effects model can enhance the empirical regression efficiency. Columns (1), (3), (5), and (7) in Table 8 shows that the impact of *EPP* on innovation efficiency is significant when control variables are excluded in the regression. Columns (2), (4), (6), and (8) include the control variables and the results are consistent.

Mediating effect test

The relationship between variables is usually not a direct causal effect, but arises through the indirect influence of one or more mediating variables. We use intermediary effect analysis to judge whether there is a variable that plays an intermediary role between the explanatory variable and the explained variable and also analyze the impact of this role. The main methods used to test for mediating effects include stepwise regression, Sobel test, and Bootstrap test (MacKinnonet al. 2002; Fritz and MacKinnon 2007; Hayes 2009). Although the stepwise regression method has the least statistical efficacy, it is more reliable when the coefficients are significant (MacKinnon et al. 2002). Therefore, we introduce a stepwise regression approach to test the mediating effect of urban form. Stepwise regression is as follows:

$$IE_{it} = \beta_0 + \beta_1 EPP_{it} + \gamma X_{it} + \Phi_t + \mu_i + \varepsilon_{it} \tag{5}$$

$$UF_{it} = \beta_0' + \beta_1' EPP_{it} + \gamma' X_{it} + \Phi_t' + \mu_i' + \varepsilon_{it}' \tag{6}$$

$$IE_{it} = \beta_0'' + \beta_1'' EPP_{it} + \beta_2'' UF_{it} + \gamma'' X_{it} + \Phi_t'' + \mu_i'' + \varepsilon_{it}'' \tag{7}$$

where β_1 is the total effect of *EPP* on *IE* in Eq. (5); β_1' is the effect of *EPP* on *UF*; β_2'' is the effect of *UF* on *IE* after controlling the independent variable *EPP*; and β_1'' is the direct effect of *EPP* on *IE* after controlling the meditating variable *UF*. According to the regression results, we calculate the indirect effect.

First, we use *FD* to measure urban form. Columns (1) and (2) in Table 9 show that the correlation between *EPP* and urban form and innovation efficiency shows a positive and significant correlation. Therefore, the indirect effect is significant and Bootstrap test is not required. The results

Table 8 Robustness test based on different regression methods

Variables	(1) OLS	(2)	(3) Bilateral truncation	(4)	(5) Bilateral winsorization	(6)	(7) High-dimensional fixed effect	(8)
EPP	0.009	0.037***	0.014**	0.090***	0.014**	0.090***	0.049**	0.049**
	(0.011)	(0.012)	(0.006)	(0.010)	(0.006)	(0.010)	(0.024)	(0.024)
Ln*G*		0.049***		0.034***		0.034***		0.004
		(0.007)		(0.007)		(0.007)		(0.008)
Ln*O*		0.058***		0.029***		0.029***		0.008
		(0.006)		(0.006)		(0.006)		(0.006)
Ln*TR*		0.029***		0.002		0.002		0.009
		(0.005)		(0.008)		(0.008)		(0.007)
Ln*TE*		0.013***		0.013***		0.013***		0.002
		(0.003)		(0.003)		(0.003)		(0.003)
Ln*EI*		−0.000		0.008		0.008		0.008
		(0.006)		(0.006)		(0.006)		(0.006)
Ln*H*		0.004***		0.004***		0.004***		0.004***
		(0.000)		(0.001)		(0.001)		(0.001)
Ln*F*		0.040***		0.026***		0.026***		0.002
		(0.004)		(0.006)		(0.006)		(0.006)
Ln*IS*		0.049***		0.037*		0.037*		0.054***
		(0.019)		(0.022)		(0.022)		(0.020)
Constant	0.407***	0.317***	0.406***	1.169***	0.406***	1.168***	0.393***	0.591***
	(0.006)	(0.086)	(0.003)	(0.090)	(0.003)	(0.090)	(0.009)	(0.120)
Observations	3047	3047	3047	3047	3047	3047	3047	3047
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

(1) Robust standard error in parentheses; (2) ***, **, and * indicate 1%, 5%, and 10% significance levels, respectively

of column (3) indicate that the direct effect is significant. Thus, the mediating effect of *FD* accounts for about 9.33% of the total effect. In columns (4)–(6) of Table 9, we measure urban form by *LPI*. The results showed that the mediating effect of *LPI* was significant, which accounts for about 4.36% of the total effect. In columns (7)–(9) of Table 9, we measure urban form by *PD* and the mediating effect of *PD* accounts for about 2.44%. Thus, there is a significant mediating effect of urban form on the effect of *EPP* on

Table 9 Mediating effect test

Variables	(1) *FD*	(2)	(3)	(4) *LPI*	(5)	(6)	(7) *PD*	(8)	(9)
EPP	0.090***	0.012***	0.099***	0.090***	0.013***	0.094***	0.090***	0.008***	0.092***
	(0.010)	(0.001)	(0.010)	(0.010)	(0.002)	(0.010)	(0.010)	(0.002)	(0.010)
UF			0.700**			0.302***			0.274**
			(0.145)			(0.084)			(0.128)
Constant	1.169***	1.483***	2.286***	1.169***	0.502***	1.017***	1.169***	0.014	1.173***
	(0.090)	(0.012)	(0.233)	(0.090)	(0.021)	(0.099)	(0.090)	(0.014)	(0.090)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3047	3047	3047	3047	3047	3047	3047	3047	3047
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

(1) Robust standard error in parentheses; (2) ***, **, and * indicate 1%, 5%, and 10% significance levels, respectively

innovation efficiency, and the mediating effect differs for different indices of urban form.

In fact, the impact of *EPP* on cities with different urban forms is heterogeneous. Existing scholars have reflected that the impact of urban forms on the urban environment is based on the impact of different types of urban morphological characteristics on energy consumption, environmental pollution, carbon emissions, biodiversity, and urban climate. For example, Marquez and Smith (1999) simulated air quality in three forms of cities: corridor, edge, and compact and found that compact cities had the smallest air pollutant emissions. When the city matures, urban form becomes denser and more compact. The accessibility of industries located in different regions will be greatly improved. This will effectively improve the regional innovation ability through the flow of innovation elements such as knowledge, science and technology, and talents. Specifically, the progress of regional terms of trade promotes the more flexible flow of scientific and technological personnel among regions, which drives the forward and backward links of industries and promotes the interaction between regions, which is the first aspect of the intermediary effect of urban form. On the other hand, there is an innovation spillover and spatial feedback effect due to the externality of space, which complies with the results of the robustness test.

Conclusions

Both the importance of environmental protection and the sustainability of innovative development have always been important topics in academic research. Based on 277 cities in China from 2006 to 2016, we implemented *EPP* as a quasi-natural experiment to explore its impact on regional innovation efficiency. We introduced DID using a continuous treatment approach. Furthermore, we examine the mediating effect of urban form. The results show that *EPP* significantly improves regional innovation efficiency. Robustness tests were conducted based on different measurements of innovation and different regression methods. Both results were consistent with the baseline results, showing *EPP* has technological innovation and diffusion effects. The mediating effect test results show that urban form has a significant mediating effect on the impact of *EPP* on innovation efficiency.

According to the results, the government should fully combine the experience of environmental governance in different economies abroad and consider the heterogeneity of different periods and economic structures. Environmental policies should be formulated precisely by continuously tracking economic and environmental data. Especially for China's industrial economy, which is in a critical period of transformation, development, and technological upgrading, it is necessary not only to emphasize technological progress, but also to make full use of the technological innovation and diffusion effect of environmental protection policies. Regional environmental policies should also focus on local geographical location, industrial structure, economic level, and even policy implementation. For developed areas along the eastern coast of China, cities tend to have high innovation vitality, close economic exchanges with neighboring cities, relatively developed technology, capital-intensive industries (e.g., information and communications), and an overall good economic foundation. Therefore, these cities are most suitable for direct environmental regulation and supervision and effectively promote the green innovation of enterprises. In less developed areas, environmental policies are relatively weak; the strength and direction of technological progress will be affected by these policies, and the output effect of green technology is often insufficient. Tough environmental policies will exacerbate the survival pressure of enterprises and have a significant impact on urban economies. The government should gradually establish softer environmental policies to guide the green innovation of enterprises through a combination of subsidies and industry standards.

Although policy evaluation is more conducive to the identification of causality, it is not a substitute for more general regularity studies. This paper evaluates the effect of *EPP*, but the design of the policy system and the insufficient implementation of the policy may affect the results, similar to the EU's emission trading system and China's sulfur dioxide trading pilot. For policymakers, comparing the innovative effects of different types of environmental policy tools has strong policy implications. However, different types of policies are difficult to compare horizontally. In addition, different policies have different targets, such as emitters or pollutants, and thus, they promote different types of technological innovation activities. Empirical research also needs to be refined and deepened in these aspects.

Author contribution All authors contributed extensively to the work presented in the paper. Conceptualization, J.Z. and H.T.; project administration, J.Z.; methodology, H.T. and M.B.; software, M.B.; writing—original draft preparation, H.T.; writing—review and editing, H.T. and M.B. All authors have read and approved the final manuscript.

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