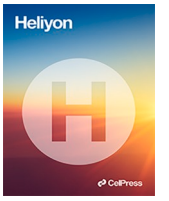
Heliyon 9 (2023) e21079

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon



Do pilot free trade zones promote green innovation efficiency in enterprises? —Evidence from listed companies in China

Guihu Wang [a,b], Yirui Hou [a,*], Shanshan Du [c], Chun Shen [d]

[a] School of Economics, Zhengzhou University of Aeronautics, No.15 Wenyuan West Road, Zhengzhou, Henan, 450018, China
[b] Institute of Finance, University of Chinese Academy of Social Sciences, No. 27 Wangfujing Street, Beijing, 100710, China
[c] School of Social Sciences, Tsinghua University, No. 1 Haidian District, Beijing, 100084, China
[d] Woosuk University, Samnye-ro 443, Jeollabuk-do, 55338, South Korea

ARTICLE INFO

Keywords:
Pilot free trade zone
Policy evaluation
Enterprise green innovation
Multi-period double differential

ABSTRACT

The establishment of the China Pilot Free Trade Zone complies with the concept of sustainable development, and its construction can not only realize trade liberalization and facilitation but also activate the green innovation momentum of enterprises to help solve China's current dilemma of sustainable development and economic growth. This paper is the first to consider the impact of the establishment of the pilot free trade zone from the perspective of enterprise green innovation efficiency, providing a direct answer to the key question of whether the construction of the pilot free trade zone can truly serve the high-quality development of the economy in the new era, and enriching the theoretical research on the enterprise green innovation efficiency macro-drivers related theoretical research. In addition, this paper uses the super-efficient EBM-GML model to measure the level of green innovation efficiency of enterprises, on the basis of this, it adopts the multi-stage differences-in-differences method used to evaluate the impact of the establishment of the pilot free trade zone on the green innovation efficiency of enterprises. According to the benchmark regression results, the establishment of the pilot free trade zone has promoted the degree of green innovation efficiency of enterprises, and this promotion effect is sustainable. This conclusion was validated by robustness tests. Heterogeneity testing confirms that the pilot free trade zone has a significant influence on the green innovation efficiency of enterprises in heavy pollution industries, non-state-owned enterprises and patent-intensive enterprises. With the enhancement of environmental regulations, the green innovation efficiency of enterprises shows significant improvements. The analysis of the transmission mechanism shows that the pilot free trade zone influences the green innovation efficiency of enterprises primarily through the cost reduction effect, tax incentive effect, and reverse technology spillover effect. This study clarifies whether the policy of the pilot free trade zone can boost the green innovation efficiency of enterprises, and provides useful insight for further implementing the strategy of opening up to the world and promoting high-quality economic growth.

1. Introduction

Resource depletion and ecological degradation have become major constraints restricting sustainable human development. Since

* Corresponding author.
E-mail address: ll17839986737@163.com (Y. Hou).

https://doi.org/10.1016/j.heliyon.2023.e21079
Received 26 February 2023; Received in revised form 5 October 2023; Accepted 15 October 2023
Available online 16 October 2023

the reform and opening up, China's economic development has made outstanding achievements but the traditional mode of production is destructive to the ecological environment, creating a dilemma between serious environmental pollution and economic growth[1]. In this context, green innovation with both environmental and economic benefits will become a new driving force for high-quality development[2]. Under the guidance of the government in recent years, Chinese enterprises are increasingly participating in green innovation activities. However, on the whole, the green patent application in China is currently characterized by large quantity and low quality, with a large gap between its level in China and the international advanced green innovation level. Companies lack the motivation and ability to conduct green R&D due to the lack of awareness on green innovation, and the high investment and complexity of green innovation. In the course of promoting sustainable economic growth, key issues are to find means for activating the green innovation efficiency of enterprises, reducing repeated low-level innovation between regions, and effectively promoting enterprises to achieve the goal of reducing energy consumption and pollution emissions. In fact, in the open economic system, although green innovation ability controls technology accumulation within an enterprise, the international advanced technology introduced by high-level opening up is considered a significant factor for enhancing the high-level green R&D ability of enterprises[3].

China's Pilot Free Trade Zone (PFTZ) is a crucial highland for China's institutional innovation and opening up. After the establishment of the Shanghai Pilot Free Trade Zone in 2013, PTFZ has undergone six expansions. Up till the end of 2022, twenty-one pilot free trade zones have been established in China, forming a new paradigm of opening up that runs through eastern, western, southern, northern, and central China. PFTZ has made bold innovations in promoting trade and investment facilitation, financial innovation, green trade, and other fields, effectively promoting regional economic development, and has become an important engine for China's economic growth. However, under the background of the continuous evolution of global economic integration, the green innovation of enterprises in some developing countries is still insufficient. It remains unclear whether PFTZ will promote trade liberalization and facilitation while positively affecting green innovation for local firms. Moreover, the potential of the establishment of PFTZ to change the traditional production mode of enterprises and achieve the dual goals of coordinating economic development and environmental protection as well as their mechanisms remain to be resolved. By clarifying these uncertainties, not only will research on the sustainable development of PFTZ be improved, but empirical support can also be provided for China to overcome institutional obstacles through high-level opening-up, activate the green innovation motivation of enterprises, and provide empirical support for achieving the goal of synergy and symbiosis of economic development and ecological protection.

The primary contributions of this study are as follows: First, Currently, discussions about China's PFTZ mostly focus on their economic benefits, while explorations about environmental benefits are very scarce, not to mention studies on how the establishment of PFTZ can improve the green innovation efficiency of enterprises, but the relationship between the two is beginning to emerge as seen in the current literature. This paper is the first to consider the impact of the establishment of PFTZ from the perspective of enterprise green innovation efficiency, which broadens the depth and breadth of research related to the environmental benefits of PFTZ, and at the same time provides empirical evidence for enterprises to seize the policy opportunities to improve their green innovation level. Second, to ensure the credibility of the estimation results, an index system of the green innovation level of enterprises is constructed from the perspective of input and output, the ultra-efficient EBM-GML model is used for measurements, and the multi-stage differences-in-differences method is employed to evaluate the impact of the establishment of PFTZ on the green innovation efficiency of enterprises. Third, the sample enterprises are classified into heavily polluting industries, patent-intensive enterprises, state-owned enterprises, and green rating enterprises for heterogeneity testing, such that the heterogeneity of the relationship between different enterprises can be better analyzed from the micro perspective. Latest, the cost reduction effect, tax incentive effect, and reverse technology spillover effect are considered as mediating variables to test the conduction mechanism between PFTZ policy and the green innovation efficiency of enterprises, and the effects of the conduction mechanism are analyzed in detail.

2. Literature review

At present, studied on promoting the green innovation level of regional enterprises in PFTZ and coordinating the relationship between economic development and environmental protection are relatively lacking. In this study, the literature review was carried out from the following three aspects.

2.1. Policy effect and existing problems of PFTZ

Since the establishment of PFTZ, scholars at home and abroad have analyzed the effect of policy implementation from both the macro and micro aspects and discussed the existing problems. On the one hand, from the macro perspective, the establishment of PFTZ has brought "institutional dividends" to the high-quality development of the regional economy[4], and significantly enhanced the long-term effect of the regional economy [5]. Firstly, the establishment of PFTZ has realized the transformation from product market opening to factor market opening [6], accelerating the free flow of factor resources, and continuously improving the economic growth rate and growth quality [7]; Secondly, PFTZ significantly promotes the role of innovation-driven promotion through institutional innovation [8], accelerates the formation of a high-level trade facilitation system and investment system through regional radiation and industrial agglomeration [9], and promotes regional economic prosperity [10]; Finally, PFTZ explores and improves the financial open innovation system, increases financial support for cross-border trade, investment, and financing, and contributes toward promoting the stable development of the real economy [6]. On the other hand, from the micro perspective, the negative list management model adopted by government departments will further improve the transparency of government management, accelerate the construction of fair and reasonable competition relations, and promote the rapid development of regional service industries [11,12]. For enterprises, the implementation of the PFTZ policy can have a strong impact on enterprise financing constraints[13], imported

intermediate goods [14], and enterprise innovation level [15]. In addition, with regard to the existing problems in PFTZ, most scholars believe that the current development of the free trade zone involves problems such as insufficient deep-seated institutional innovation [16], a gap exists in the development of international economic and trade rules [17], and the leading effect of development is not clear [18].

2.2. Influencing factors of enterprise green innovation

Most research on the influencing factors of enterprise green innovation is based on the perspective of external environmental pressure and the perspective of internal resource utilization[19,20]. Enterprise green innovation is an environmental protection innovation activity with the primary goal of reducing environmental burden and improving the ecological environment, including green product design, energy conservation, emission reduction, green technology development, and other related innovations[21,22]. On the one hand, from the perspective of external environmental pressure, some scholars have proved that environmental regulatory pressure and stakeholder pressure are the main sources of external environmental pressure[23], which will significantly affect the green innovation of enterprises[24]. At the same time, under the influence of the same group effect, the green innovation behavior of other enterprises will also exert competitive pressure and legal pressure on enterprises[25], and promote enterprises to continuously learn and imitate the green innovation behavior of competitors to improve their green innovation level[26]. In addition, the level of regional integrity also affects the green innovation efficiency of enterprises[27]. On the other hand, from the perspective of internal resource utilization, some scholars have proved that green innovation is the key to maintaining a competitive advantage of enterprises [28], and internal factors such as internal absorption capacity[29], knowledge sharing ability[30], corporate culture, corporate executives' awareness on environmental issues[31], and innovative technology and ability [32] will all play a driving role in corporate green innovation. The digital level of enterprises and digital technologies including big data, the Internet of Things, blockchain, and other technologies will not only promote information sharing and knowledge integration but also significantly improve the green innovation level of enterprises[33–35]. This paper argues that corporate green innovation and environmental development are closely related, and defines the relationship between green innovation and sustainability as a strategic form of corporate sustainability through the introduction of new ideas, behaviours, products and processes to reduce negative impacts on the environment. In addition, some scholars have explored the impact of changes in the external policy environment on enterprise green innovation from the perspectives of low-carbon city pilot policy[36], green credit policy[37], and carbon emissions trading policy[38].

2.3. Environmental effects of PFTZ

There are not many pertinent studies on the effects of PFTZ on enterprise green innovation efficiency, and only few studies have reported on the environmental impact of PFTZ from multiple perspectives. However, there is no consensus on the conclusions of these studies. On the one hand, according to experts such as Grossman and Krueger[39], the environmental quality of free trade zones will significantly deteriorate as construction progresses. According to the pollution haven hypothesis, trade liberalization will exacerbate environmental issues in developing nations, forcing developing countries to become "pollution havens" [40]. Chung[41] confirmed the behavior of pollution havens using a sample of Korean multinationals, while Managi[42] empirically demonstrated that trade liberalization will aggravate environmental pollution in non-OECD countries and increase CO2 and SO2 emissions. On the other hand, the simple factor endowment hypothesis contradicts the pollution haven hypothesis. It posits that factor endowment flow is the decisive factor controlling trade flows, rather than the cost of corporate pollution[43], and the establishment of free trade zones can effectively alleviate the contradiction between factor demand and resource supply, and optimize the environment by promoting technological progress. The causal effects of foreign trade and economic benefits will improve environmental quality[44]. Werner[45] subdivided trade effects into scale, technology, and structural effects, and confirmed that the establishment of free trade areas is beneficial to environmental improvement. Dean[46] used Chinese water and air pollution data to confirm that China's foreign trade reduces pollution levels, disproving the pollution haven hypothesis. At the same time, there is a virtuous circle relationship between the sustainable development goals of the region and the green innovation development of enterprises. On the one hand, in the context of sustainable development, enterprises show positive willingness to green technological innovation. Driven by the intrinsic motivation of enterprises, local enterprises continuously carry out green innovation and green management[47,48]. On the other hand, green innovation by enterprises will be able to effectively improve the environment[49,50], and advance the continuous improvement of regional sustainable development. Therefore, we believe that the call for environmental protection initiatives specifically proposed in the FTZ master plan will encourage enterprises to accelerate green transformation, improve the efficiency of green innovation in enterprises, and advance the realization of regional sustainable development goals.

In summary, although preliminary studies have been carried out on the environmental benefits of PFTZ, there is no consensus on the environmental impacts of PFTZ establishment, and only few studies have used empirical methods to analyze the impact of PFTZ as a macro policy factor on the green innovation level of micro-entities of enterprises. Most existing relevant studies analyzed the impact of PFTZ on the green innovation of enterprises from a qualitative perspective, and some relevant empirical analysis methods also need to be improved. Therefore, this study employed the multi-stage differences-in-differences method to analyze the impact of PFTZ establishment on enterprise green innovation, intending to compensate for the shortcomings in existing literature.

3. Institutional background and theoretical hypotheses

3.1. Institutional background

Adhering to a high level of opening up to the outside world is one of the important experiences of China's economic development [51]. China's opening up commenced with the Southern Special Economic Zone, which introduced the concept of a market economy and became a model for inland reform. Unlike the "policy depression" of special economic zones, the establishment of PFTZ is expected to force reform through opening up, form a replicable and generalizable international trade system, facilitate a high level of opening up, and contribute "institutional dividends" to high-quality economic growth in the zone[4]. At present, PFTZ has been successively established in 21 provinces and cities in China, with continuous innovations in the financial system, trade supervision system, administrative management system, and service industry development level, forming a highland of institutional reform.

By sorting out green development policies of PFTZ, "adhering to ecological priority and promoting green and low-carbon development" appears to always have been one of the main themes in the construction of pilot zones. PFTZ has achieved good results in promoting green and low-carbon development, ecological environment governance, and international cooperation. As of July 2021, the implementation plans of the existing 21 pilot free trade zones have put forward relevant requirements and targets for ecological environmental protection. There are over 90 articles on the ecological environment, the majority of which support high-quality local development. More than 20 articles have been framed on the prevention of environmental risks, such as "development and utilization must comply with ecological environment requirements" and "ecological environment risk prevention". In addition, there are more than 20 innovative environmental policies, such as "low-carbon certification of export products", "responsibility reporting system and responsibility traceability system". These policies for green development are conducive to guiding PFTZ to improve environmental protection and support the complete green transformation of economic and social development.

3.2. Theoretical hypotheses

The institutional innovation of PFTZ has the potential to alter the distribution of regional income and increase resource efficiency [52], and effective institutional design can further motivate enterprises toward green innovation. On the one hand, PFTZ increases the constraints of informal systems such as environmental public opinion pressure on corporate behavior, increases the law's disclosure of corporate environmental information, maximizes public participation in environmental evaluation, and places a high value on ecological environmental protection. Under the influence of the informal system, ethical-driven enterprises enhance their awareness of social responsibility, guide the allocation of resources along a favorable direction for society, and boost the enthusiasm of enterprises for green innovation[53]. To build a positive corporate image and obtain investors' trust to gain a market advantage, profit-driven enterprises continuously strengthen investment in green innovation and encourage the growth of green innovation within businesses. In contrast, PFTZ has innovated environmental regulation models by implementing more than 20 innovative environmental policies such as the green product list system and the responsibility reporting system, as well as 11 types of green management measures such as source reduction and optimization of environmental impact assessment management. According to the "Porter hypothesis"[54], when confronted with a high level of environmental regulation, enterprises urgently need to improve their production efficiency in order to fully stimulate green innovation capabilities. The green barriers set up by enterprises to meet PFTZ will increase additional expenses including one-time compliance costs and repeated compliance costs. In order to prevent the loss of price advantage, enterprises lacking environmental protection technology and poor capital circulation continue to enhance the level of green technology and improve their green innovation efficiency. Based on the aforementioned analysis, hypothesis 1 (H1) is proposed.

H1. The establishment of PFTZ will significantly increase the green innovation efficiency of enterprises

In the context of institutional innovation, the contribution of PFTZ to elevating the green innovation efficiency of enterprises primarily is manifested as three effects: cost reduction effect, tax incentive effect, and reverse technology spillover effect.

3.2.1. Cost reduction effect

PFTZ effectively reduces the cost of green innovation through financial system innovation and encourages enterprises to continuously participate in green innovation activities. From the point of view of reducing financing costs: Firstly, PFTZ explores the convertibility of RMB capital accounts, interest rate liberalization, and cross-border use of RMB, innovates external financing models, provides convenient financing services for Chinese enterprises to develop abroad, and enables enterprises to have sufficient external funds as support in the process of operation[55,56]; Secondly, PFTZ realizes "bank-government interconnection" through the distributed sharing mode, which combines the tax credit and financing rating of enterprises to help enterprises quickly pass tax audits, improve financing efficiency, and reduce financing costs[57].; Finally, PFTZ promotes the development of green finance business, provides support for the construction of resource emission reduction trading institutions, and extensively carries out green securitization, green bond, green equity investment, and financing business, to continuously improve the green financial service system[58]. From the perspective of reducing enterprise management costs: the establishment of the PFTZ not only reduces government intervention and creates a fair market environment, but also facilitates enterprise development by simplifying market processes. On the one hand, the continuous improvement of the market mechanism and the rapid development of Fintech provides convenience for enterprise development, reduces the cost of enterprise operation and management, enables enterprises to have more funds to invest in the process of technology research and development, and improves the green innovation efficiency of enterprises [59]. On the other hand, the pilot policy of the FTZ can directly enhance the attraction of advanced management talents, promote the pooling of innovative

management talents, absorb the advanced enterprise management mode, further reduce enterprise management costs, and promote the enhancement of enterprise green innovation efficiency. Based on the aforementioned analysis, hypothesis 2 (H2) and hypothesis 3 (H3) is proposed.

H2. The establishment of PFTZ will significantly increase the green innovation efficiency of enterprises by reducing the cost of corporate financing

H3. The establishment of PFTZ will significantly increase the green innovation efficiency of enterprises by reducing the cost of corporate management

3.2.2. Tax incentive effects

PFTZ implements tax relief policies for policy-supported industries, enterprise import and export trade, and enterprise talent training, and further enhances the green innovation efficiency of enterprises through tax incentives. On the one hand, PFTZ provides tax exemptions and exemptions for cross-border e-commerce and other policy support industries, implements policies such as value-added tax, consumption tax, and export tax rebates, effectively reduces the actual tax level of enterprises, reduces the operating costs of enterprises, and encourages enterprises to achieve sustainable development through green innovation. On the other hand, PFTZ implements preferential tax policies in the fields of investment and trade, scientific and technological innovation, and talent introduction[60]. PFTZ encourages enterprises to engage in scientific and technological innovation activities and enjoy tax exemption or tax rebate for the import of scientific research equipment from R&D institutions in PFTZ, which effectively reduces the actual tax payment of enterprises, easing their financial constraints, and promotes continuous green innovation. A certain amount of income tax relief will be granted to high-tech personnel working in enterprises within PFTZ, which is conducive to the absorption of high-tech talents by enterprises, raising their technical level, and encouraging green innovation. Based on the aforementioned analysis, hypothesis 4 (H4) is proposed.

H4. The establishment of PFTZ will significantly increase the green innovation efficiency of enterprises through tax incentives

3.2.3. Reverse technology spillover

By strengthening the spillover effect of reverse technology, the establishment of PFTZ can boost green innovation efficiency in enterprises. Following the endogenous growth theory, host countries can narrow the technological gap with developed countries by strengthening cross-border investment and international trade. PFTZ has transformed the government management model from a "positive list" to a "negative list", accelerated enterprise integration into the global production network, and enabled timely access to advanced knowledge and technical resources to improve its innovation ability. PFTZ attracts more sophisticated foreign investors who introduce mature operating concepts to enterprises to improve their tolerance for innovation failure[61,62]. At the same time, PFTZ requires enterprises to disclose information, which strengthens the public's supervision of green innovation of enterprises and further promotes the improvement of the level of green innovation of enterprises. Therefore, the establishment of PFTZ will improve the competitiveness of enterprises and the level of social supervision, improve the effectiveness of enterprise resource utilization and green innovation, and encourage enterprises to continuously raise their level of technological innovation. Based on the above theoretical analysis, hypothesis 5 (H5) is proposed.

H5. The establishment of PFTZ will significantly increase the green innovation efficiency of enterprises through reverse technology spillovers

The theoretical analysis framework of this study is depicted in Fig. 1.

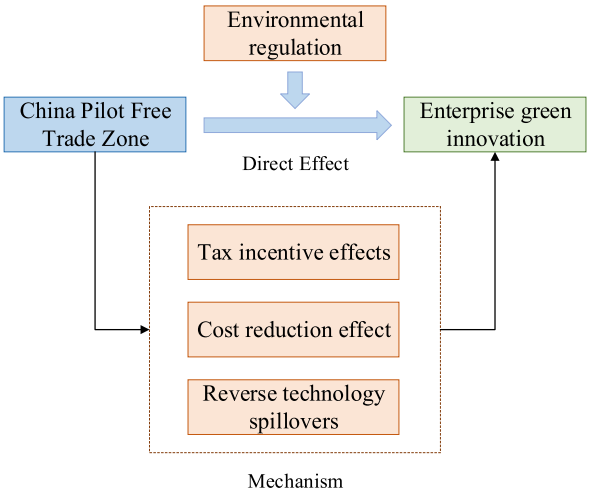


Fig. 1. Impact mechanism of PFTZ on enterprise green innovation efficiency.

4. Methods and data

4.1. Model

To determine how PFTZ affects the green innovation efficiency of enterprises, this study employed a multi-period differences-in-differences model for testing. Accordingly, the specific DID model is:

$$GTFP_{it} = \alpha_0 + \beta_0 treat_i \times post_t + \gamma_0 \sum cov_{it} + \delta_i + \mu_t + \varepsilon_{it} \quad (1)$$

Among them, The green innovation level of i businesses in year t is shown by $GTFP_{it}$. The interaction item $treat_i \times post_t$ represents the net effect of policy implementation, where $treat_i$ is a grouped dummy variable and $post_t$ is a time dummy variable. Cov_{it} represents control variables, including control variables at the enterprise and region levels. ε_{it} is a random perturbation term, δ_i represents the enterprise fixed effect, and μ_t represents the time fixed effect. According to the basic definition of independent variables, the coefficient β_0 in Equation (1) represents the average effect treatment of PFTZ-induced changes in the level of green innovation efficiency of enterprises.

Equation (2) and Equation (3) are established to confirm the existing mediating effect based on the equation above, which reflects the direct influence mechanism of PFTZ on the level of green innovation efficiency among businesses. To validate the roles of the cost reduction effect, tax incentive effect, and reverse technology spillover effect in elevating green innovation efficiency among businesses in PFTZ, this study adopts the mediation effect test procedure that was developed by Wen and Ye[63]. For brevity, M_{it} is used to represent the above variables separately. Based on the model design, the two following models are proposed in this paper to test the relationship between variables:

$$M_{it} = \alpha_1 + \beta_1 treat_i \times post_t + \gamma_1 \sum cov_{it} + \delta_i + \mu_t + \varepsilon_{it} \quad (2)$$

$$GTFP_{it} = \alpha_2 + \beta_2 treat_i \times post_t + \lambda_2 M_{it} + \gamma_2 \sum cov_{it} + \delta_i + \mu_t + \varepsilon_{it} \quad (3)$$

At the same time, to further study the heterogeneous impact of moderating factors such as the type of environmental regulation of enterprises on PFTZ to improve the green innovation efficiency of enterprises, command-based environmental regulation, public participation environmental regulation, and the multiplication terms of these two variables and policy shocks based on Equation (1) are added to construct Equation (4). If $\alpha_5 > 0$, environmental regulation has the potential to significantly enhance the role of PFTZ in raising the green innovation efficiency of enterprises. The specific model design is as follows:

$$GTFP_{it} = \alpha_3 + \beta_3 treat_i \times post_t + \alpha_4 X_{it} + \alpha_5 X_{it} \times treat_i \times post_t + \gamma_3 \sum cov_{it} + \delta_i + \mu_t + \varepsilon_{it} \quad (4)$$

4.2. Variable selection

4.2.1. Dependent variable

Referring to the approach of Tone and Tsutsui [64], the EBM-GML index, a super-efficient model with variable scale returns, is used to express the green innovation efficiency of businesses and to measure their green total factor productivity. The green total factor index of enterprises includes the input indicators and outputs of enterprises, namely: (1) Input elements. According to the theory of production function, the input indicators of enterprises involve labor input and capital input. Drawing on the research of Liu[65] and other scholars, capital investment is measured by capital stock, and the capital stock is calculated using the perpetual inventory method with a 5 % depreciation rate. The number of employees employed by the business at the end of the year is used to represent labor input. (2) Expected output. The expected output is expressed in terms of business revenue. (3) Undesired outputs. Undesired output is expressed using corporate CO_2 emissions. By calculating the adjustment coefficient w_j of pollution indicators of various industries in a city, the amount of polluting emissions in various industries in the city is determined, and the CO_2 emissions of k enterprises in the j industry of i city are finally obtained.

The method of Cui and Lin[66] is applied and subdivided to the industry level, in which $W_{ij} = (P_{ij}/\sum P_{ij})/(O_{ij}/\sum O_{ij}) = (P_{ij}/O_{ij})/[(\sum P_{ij})/(\sum O_{ij})]$, P_{ij} represents the CO_2 emissions of the j industry in i city, $\sum P_{ij}$ represents the total CO_2 emissions of the national j industry, O_{ij} represents the total value of the j industry's output in i city, and $\sum O_{ij}$ is the national j industry's total output value. The weighted adjusted output of the j industry of i city is $em_{ij} = W_{ij}{}^{*}Y_{ij}$, where Y_{ij} is the CO_2 emissions of the j industry of i city. Finally, the pollutant emissions of enterprises in the j industry of i city were determined as $em_{kij} = em_{ij} \times (Q_k/\sum Q)$, where Q_k is the output value

Table 1
Input-output indicator system.

Target layer	Guidelines layer	Metrics layer	unit
Input	Capital investment	Capital stock	million dollars
	Labor input	Employees	piece
Output	Expected output	Operating income	million dollars
	Undesired output	CO_2 emissions	ton

of *k* enterprise, and *Q* is the total output value of the *j* industry in *i* city. The data of undesired outputs were obtained from the Guotai Carbon Neutrality Database. Table 1 depicts the specific construction of the indicator system:

4.2.2. Independent variable

The independent variable in this study is whether the company includes the PFTZ dummy variable ($post_{it} \times treat_{it}$), if the region where enterprise *i* is located becomes a PFTZ in year *j*, we assign the value of PFTZ to 1; otherwise, we assign the value of PFTZ to 0.

4.2.3. Mediating variables

The following mediating variables were established for this study, which were determined by the previous analysis: (1) Cost reduction effect (RZ). The reduction of enterprise financing cost is used to express the cost reduction effect of enterprises, where RZ = enterprise interest expense/total liabilities of enterprises (total liabilities of enterprises = long-term liabilities +current liabilities); (2) Tax incentive effect (JS). Corporate tax incentives are represented by the effective income tax ratio, where js = ln(100 * income tax expense/total profit); (3) Reverse technology spillover effect (CX). The reverse technology spillover effect is measured using the logarithm of current R&D investment.

4.2.4. Modulating variables

In this study, the types of environmental regulation were divided into command-based environmental regulation (ML) and public participation environmental regulation (GZ). The proportion of regional environmental pollution control investment to GDP and the logarithm of environmental pollution petitions were used as proxy variables for the two types of environmental regulation in order to investigate the relationship between the establishment of PFTZ and green innovation efficiency in businesses.

4.2.5. Control variables

(1) Enterprise-level Control variables: ① Workforce (Workforce), measured by the logarithmic number of employees in the enterprise; ② Concurrent (Concurrent), with a value of 1 if the chairman and general manager are the same person, and a value of 0 otherwise; ③ Enterprise scale (scale), measured by the logarithm of the total assets of the enterprise; ④ Age of the enterprise (age), measured by the number of years since the establishment of the enterprise; ⑤ Capital intensity (Density), measured by the ratio of total assets to operating income; ⑥ The shareholding ratio of the largest shareholder (Sharehold), measured by the proportion of shares held by the largest shareholder to the total share capital; ⑦ Enterprise growth (tobinq), measured by the market value of the enterprise and the proportion of total assets; ⑧ Earnings per share (earn), measured by the proportion of net profit and equity of the enterprise. (2) City-level control variables: ① Air pollution (PM10), expressed as the logarithm of the annual average concentration of inhalable fine particulate matter; ② regional economic development (pergdp), expressed in per capita gross regional product, which is deflated using the 2010 price index as the base period; ③ Industrial structure (ind), measured by the ratio of the output value of the tertiary and secondary industries; ④ financial development (finance), measured by the proportion of financial institutions' year-end deposit and loan balances to GDP; ⑤ Expenditure on education and technology (Scedu), measured by the proportion of education and science and technology investment in local fiscal expenditure; ⑥ population size (people), measured by the logarithmic number of the permanent population at the end of the region; ⑦ Level of scientific and technological development (TEC), measured by the proportion of

Table 2
Descriptive statistics.

	Name	Mean	SD	Min	Max
Dependent variable	GTFP	0.9642	0.2145	0.0011	2.9912
Independent variable	treat*post	0.1456	0.3527	0	1
Mediating variables	rz	0.0026	0.0025	0.0005	0.0074
	js	2.7385	0.8857	−9.7749	4.4206
	cx	17.7279	1.7791	5.0938	26.3143
Modulating variables	ML	1.1962	0.7429	0.0200	3.500
	GZ	5.8795	0.2157	4.4427	5.9314
Enterprise-level Control variables	workforce	7.7764	1.3086	2.1972	13.2228
	concurrent	0.2391	0.4265	0.0000	1.0000
	scale	22.3574	1.3604	14.7586	28.6365
	age	2.2814	0.7753	0.0000	3.4340
	density	0.3559	0.4143	−0.0333	9.4915
	sharehold	34.3495	15.1715	0.2900	99.0000
	tobinq	2.3270	1.8228	−1.1813	48.5051
	earn	0.3762	0.9442	−22.8260	44.3565
City-level Control variables	PM10	3.7417	0.4039	0.8473	5.6312
	pergdp	11.0511	1.0878	5.4299	15.8163
	ind	1.5431	1.0472	0.1090	5.3500
	finance	1.5551	0.6621	0.4280	3.4500
	scedu	0.0316	0.0116	0.0080	0.1950
	people	6.7196	0.7536	3.1440	8.0740
	tec	0.0314	0.0312	0.0040	0.1160
	innovation	7.5916	1.7437	0.0000	10.4536

employees in the regional computer software and software industry; ⑧ Regional green level (innovation), measured by the logarithm of the number of urban green patent applications.

4.3. Data source

In this study, companies listed on the Shanghai and Shenzhen stock markets in China between 2010 and 2021 were used as the initial research samples. The data were processed as follows: (1) Exclude enterprises that are missing key financial variables; (2) Exclude enterprises that were treated by ST or *ST and delisted or listed during the sampling period; (3) Exclude financial enterprises; (4) Exclude enterprise data with a sampling period of less than 10 years. Finally, 25237 observations were obtained, covering 2177 listed companies. Data on the listed companies considered in this study were acquired from the CSMAR database, the patent data of listed companies were from the China National Intellectual Property Administration, and annual city data were obtained from the "China Urban Statistical Yearbook". To control the influence of individual enterprises, time factors, and industry factors on the results, the enterprises effect, the year effect, and the industry effect were fixed at the same time. In addition, to avoid the influence of data outliers on the test results, we winsorize the data at the 1 % level.

Descriptive statistics for the main variables are presented in Table 2. The maximum and minimum green innovation efficiency of the sample enterprises were 2.9912 and 0.0011, respectively, and the average value was 0.9642, indicating that enterprises' green innovation efficiency needs to be improved at this point and that this study has some practical significance. In addition, the variance inflation factor (VIF) and correlation coefficient matrix tests both showed no severe multicollinearity between the variables, indicating that the variables selected in this study are appropriate, and this content will no longer be displayed due to space limitations.

Table 3
Baseline regression results.

	(1)	(2)	(3)
	GTFP	GTFP	GTFP
treat*post	0.0083*	0.0088**	0.0093**
	(0.005)	(0.004)	(0.005)
workforce		−0.0102***	−0.0103***
		(0.003)	(0.003)
concurrent		−0.0040	−0.0061
		(0.004)	(0.004)
scale		0.0017	0.0020
		(0.003)	(0.003)
age		0.0842***	0.0828***
		(0.004)	(0.004)
density		0.0142***	0.0125***
		(0.004)	(0.004)
sharehold		−0.0167***	−0.0180***
		(0.006)	(0.006)
tobinq		−0.0021**	−0.0016*
		(0.001)	(0.001)
earn		−0.0030*	−0.0033*
		(0.002)	(0.002)
PM10			−0.0132*
			(0.007)
pergdp			0.0009
			(0.002)
ind			−0.0207***
			(0.004)
finance			0.0099**
			(0.005)
scedu			−0.3446
			(0.248)
people			−0.0286**
			(0.013)
tec			0.1501**
			(0.061)
innovation			0.0051
			(0.005)
Constant	0.7816***	0.7697***	0.9902***
	(0.004)	(0.067)	(0.105)
Observations	25,237	24,328	23,101
R-squared	0.343	0.362	0.362
Enterprise FE	YES	YES	YES
Year FE	YES	YES	YES

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

5. Empirical results and analysis

5.1. Benchmark regression

The benchmark regression results of the impact of the PFTZ establishment on the green innovation efficiency of businesses are presented in Table 3. The regression result is shown in column (1) without the control variable, column (2) with the enterprise-level control variables, and column (3) with the city-level control variables. All three groups of regression were controlled for enterprise fixed effects, year fixed effects, and industry fixed effects. Regardless of whether the control variables at the enterprise-level or the city-level are included in the regression, it is evident from the results that the multiplier coefficient is significantly positive. This suggests that the establishment of PFTZ effectively enhances the green innovation of businesses. In economic terms, after the establishment of PFTZ, the level of green innovation efficiency of local enterprises increased by 0.93 %.

5.2. Robustness tests

5.2.1. Replacement of the dependent variable

After changing the dependent variable, the regression results are shown in Table 4 in columns (1) and (2). There are many indicators for measuring the green innovation efficiency of enterprises, among which the number of green patent authorizations is the more commonly used. Therefore, the dependent variables were replaced by the number of enterprise green invention applications (FM), green utility model patent applications (SY) and number of green patents obtained (ZL) for robustness testing. After changing the dependent variable to the number of green innovation applications submitted by firms, the number of green utility model patent applications and the number of green patents granted to firms, the regression results are shown in columns (1), (2) and (3) of Table 4. These results indicate that the establishment of PFTZ significantly increased the green innovation efficiency of businesses.

5.2.2. Addition of the dependent variable lag term

The regression results with the lagging term of the dependent variable are shown in column (4) of Table 4. The results show that the regression coefficient of the multiplication term is still significantly positive at the level of 5 %, further proving the validity of the hypothesis.

5.2.3. Industry adjustments for the dependent variable

To mitigate the effect of industry trends on the results, the paper runs the regressions again controlling for industry x-year fixed effects. The final results are shown in column (5) of Table 3, again proving Hypothesis 1.

5.2.4. Exclusion of other alternative explanations

① Environmental credit rating policy ($treat^1$*$post^1$). Since 2013, 20 provinces (cities) in China have implemented environmental credit rating (ECR) policies in an orderly manner over five years because the implementation times of the two policies somehow overlap, which may affect the green innovation behavior of businesses. If the region where enterprise *i* is located implemented ECR policies in year *j*, we assign the value of the ECR to 1; Otherwise, we assign the value of ECR to 0, and it was included in the regression model. The final result also excludes this interference, as presented in column (6) of Table 4. ② "Belt and Road" construction ($treat^2$*$post^2$). As some cities are both PFTZ pilot cities and cities along the "Belt and Road", policy overlay effects may interfere with the results of this study. If the region where enterprise *i* is located cities along the route in 2013 and subsequent years, we assign the

Table 4
Robustness test.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	FM	SY	ZL	GTFP	GTFP	GTFP	GTFP	PSM-DID
treat*post	0.3927*	0.1112**	0.3728*	0.0087**	0.0117**	0.0094**	0.0093**	0.0097**
	(0.238)	(0.054)	(0.207)	(0.004)	(0.005)	(0.005)	(0.005)	(0.005)
L.GTFP				0.0568***				
				(0.007)				
$treat^1$*$post^1$						−0.0011		
						(0.004)		
$treat^2$*$post^2$							0.0076	
							(0.006)	
Constant	−7.1757	1.9153	−4.7713	0.9684***	1.1400***	0.9890***	0.9977***	0.9431***
	(4.459)	(19.682)	(4.823)	(0.107)	(0.118)	(0.105)	(0.105)	(0.084)
Control variables	YES	YES	YES	YES	YES	YES	YES	YES
Observations	23,101	23,101	23,101	21,569	23,101	23,101	23,101	22,215
R-squared	0.002	0.005	0.009	0.378	0.174	0.362	0.362	0.358
Enterprise FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES		YES	YES	YES
Industry FE					YES			

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

value of the "Belt and Road" to 1; Otherwise, we assign the value of "Belt and Road" to 0, and they were included in the regression model. The final results are presented in column (7) of Table 4, which further supports the previous assertion.

5.2.5. PSM + DID test

The establishment of PFTZ is not random, and PFTZ is easier to set up in areas with better economic development and convenient transportation. However, if randomness is not taken into consideration, the impact of PFTZ establishment on the green innovation efficiency of businesses will be biased. In this study, the data were matched using the propensity score matching technique to better manage and control the effects of sample selection bias as well as endogenous issues on the results. Specifically, enterprises in PFTZ established in the region with preexisting enterprises during the sampling period were selected as the treatment group, the control variable in the basic regression was set as the covariate, and year-by-year matching was applied according to the sampling method of 1:4 nearest neighbor matching putting back. The PSM-DID method is supported by the test results, which indicate that there is no significant difference in the mean of the experimental group and the control group after matching. The PSM-DID regression results are shown in Table 4, column (8). These results show that, after matching, the PFTZ establishment has a significant positive impact of 5 % on the green innovation efficiency of businesses, which further supports the empirical conclusion of this study.

5.2.6. Placebo test

In order to guarantee the rationality and accuracy of the settings for the treatment group and control group, random sampling was applied to construct a dummy treatment group and a control group for placebo testing. The specific methodology is as follows: if there are n enterprises in the region where the company is located in the t year, n companies are randomly selected from enterprises outside PFTZ in the year as a new treatment group, and the new sample is used for re-estimation. The process are repeated 1000 times, and the distribution of the 1000 results is shown in Fig. 2. The coefficient estimates of the 1000 regression results were all found to be around 0 with an approximately normal distribution, indicating that other non-observed factors do not have a significant impact. Therefore, it can be counterfactually proved that the establishment of PFTZ can boost the green innovation efficiency of businesses.

5.2.7. Parallel trend test

The differences-in-differences model needs to satisfy the parallel trend hypothesis, i.e., it needs to be shown that the treatment and control groups had the same trend before the PFTZ was established. Therefore, the dynamic impact of PFTZ on the green innovation efficiency of businesses was further investigated. Fig. 3 shows the specific results, which satisfies the parallel trend hypothesis by demonstrating that there was no significant difference in the green innovation efficiency between the treatment and control groups before the implementation of PFTZ. In addition, three years after the implementation of the policy, the impact of PFTZ on enterprises' green innovation efficiency is still significantly positive, indicating that the establishment of PFTZ has a lasting impact on enterprises' green innovation efficiency. With the advantages of open system, national policy support and free flow of resources in the zone, the green innovation level of enterprises in the PFTZ region has been rapidly improved. At the same time, the enhancement of enterprises' green innovation efficiency also improves the sustainable development level of the region through technological spillover, which promotes the development of the whole test zone into a virtuous circle accumulation and further promotes the enhancement of enterprises' green innovation efficiency, so the implementation of the PFTZ policy has a certain degree of durability. It is worth noting that it takes a period of time for the effect of policy implementation to appear, so in the year of policy implementation, the green innovation efficiency of enterprises was not significantly improved (i.e., see Fig. 3).

5.3. Heterogeneity analyses

5.3.1. Heterogeneity analysis of industry factor intensity

To examine the differences in the green innovation efficiency of enterprises in heavily polluting and non-heavy polluting industries

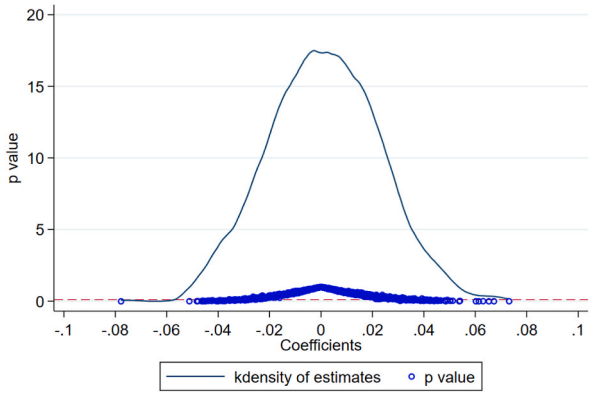


Fig. 2. Placebo test.

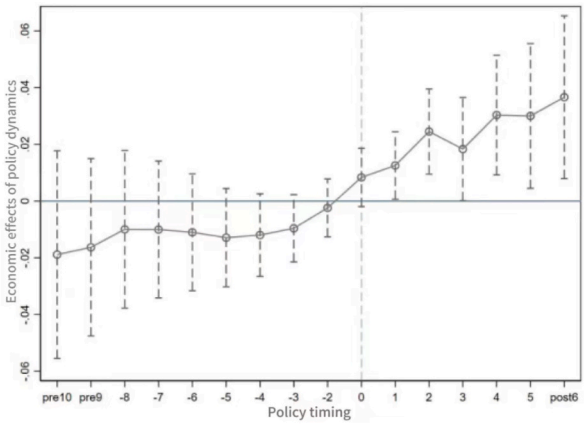


Fig. 3. Parallel trend test.

after the establishment of PFTZ, the samples were classified into heavily polluting industries (WR = 1) and non-heavy polluting industries (WR = 0) according to the Guidelines for "Environmental Information Disclosure of Listed Companies" (Draft for Comments) publicly released by the Ministry of Environmental Protection of the People's Republic of China in 2010. The results in columns (1) and (2) of Table 5 show that after PFTZ was implemented, the green innovation of enterprises in heavily polluting industries has been significantly improved, but the green innovation effect of enterprises in non-heavy polluting industries is not significant. The possible reason is that heavy-polluting enterprises themselves are sensitive to environmental pressure, and after the establishment of PFTZ, enterprises in heavy-polluting industries face greater pressure from the government and investors and take higher risks. In addition, carrying out green innovation R&D activities can minimize the production costs of enterprises and drive the strategic goals of the long-term development of enterprises through innovation. As a result of the establishment of PFTZ, heavily polluting enterprises are more motivated to carry out green innovation, and the level of green innovation improvement is more significant, which is consistent with the existing literature[67].

In addition, to determine whether the promoting effect of the establishment of PFTZ on the green innovation efficiency of enterprises is attributable to the inherent technical advantages of the issuer, the sample was divided into patent-intensive enterprises (ZL = 1) and non-patent-intensive enterprises (ZL = 0), according to the "Statistical Classification of Intellectual Property-Intensive Industries" that was published by the National Bureau of Statistics of China in 2019. The specific results of this examination are presented in Table 5. As indicated by the results in columns (3) and (4) of Table 5, after the establishment of PFTZ, the green innovation of enterprises in patent-intensive industries has increased significantly by 5 %, but that of non-patent-intensive industries is lower. And the test of inter-group differences based on the likelihood of non-correlation model shows a p-value of 0.0002 less than 0.001. Therefore, the promoting effect may be attributable to the inherent technical advantages of the issuer.

5.3.2. Heterogeneity analysis of enterprise characteristics

As state-owned enterprises (CQ = 1) and non-state-owned enterprises (CQ = 0) vastly differ in terms of resource access and government connections, even under the same policy, different types of enterprises may have different levels of green innovation efficiency. The impact of PFTZ policies on the level of green innovation among businesses with different property rights is reported in columns (1) and (2) of Table 6. The findings show that the PFTZ policy has significantly enhanced the green innovation efficiency of non-state-owned businesses. In contrast, the PFTZ policy does not have a significant impact on the green innovation efficiency of state-owned businesses. The possible reason is that non-state resources are more efficient, factor flows are more flexible, and market information can be used more effectively to improve their green innovation. This conclusion is in agreement with the findings of scholars

Table 5
Heterogeneity test at the industry level.

	(1)	(2)	(3)	(4)
	WR = 1	WR = 0	ZL = 1	ZL = 0
treat*post	0.0172**	−0.0031	0.0177**	0.0093*
	(0.009)	(0.005)	(0.009)	(0.006)
Constant	0.7040***	1.2846***	19.6871***	0.9779***
	(0.188)	(0.135)	(7.195)	(0.126)
Control variables	YES	YES	YES	YES
Observations	7389	15,712	7878	15,223
R-squared	0.355	0.370	0.393	0.331
Enterprise FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

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

Table 6
Firm-level heterogeneity testing.

	(1)	(2)	(3)	(4)
	CQ = 1	CQ = 0	ESG = 1	ESG = 0
treat*post	0.0032	0.0113*	0.0019	0.0182***
	(0.006)	(0.007)	(0.006)	(0.007)
Constant	0.7039***	1.4501***	0.7363***	1.1868***
	(0.135)	(0.169)	(0.164)	(0.154)
Control variables	YES	YES	YES	YES
Observations	12,613	10,488	10,509	12,592
R-squared	0.321	0.427	0.350	0.389
Enterprise FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES

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

such as [68,69].

PFTZ policies may have a differential impact on enterprises with different ESG ratings. Accordingly, the ESG score of China Securities was taken as an indicator to measure corporate ESG, and the average ESG score of enterprises in the sampling period was taken as a proxy variable. The top 1/2 of the enterprises were assigned a value of 1 (ESG = 1), and the bottom 1/2 were assigned 0 (ESG = 0). The impact of PFTZ policies on the green innovation efficiency of enterprise with different ESG ratings is reported in columns (3)–(4) of Table 6. The results show that the effect of the PFTZ policy on the green innovation efficiency of enterprises with higher ESG scores is not significant. Meanwhile, the effect of the PFTZ policy on the green innovation efficiency of enterprises with lower ESG scores is significantly positive at the 1 % level, and the regression coefficient is 0.0182. This result suggests that the PFTZ policy has a more significant incentivizing effect on firms that have poorer performance in terms of their ESG levels. The possible reason for this result is that after the establishment of PFTZ, corporate behavior is subject to stronger external monitoring, and there is more pressure from the government, the public, and investors on firms with lower ESG ratings. Enterprises with poorer environmental performance are more motivated to reduce carbon emissions by adopting cleaner energy sources and developing low energy-consuming production methods, etc., to improve the efficiency of their own green innovations, build a favorable image, and strengthen their competitive advantages in the process of opening up to the outside world, and to win the trust and support of stakeholders for the long-term development of their enterprises.

5.3.3. Moderating effects test

Considering the large gap in the level of urban environmental regulation in China, many scholars have introduced environmental regulation in their research to clarify the potential impact of environmental regulation on the connection between corporate green innovation efficiency and PFTZ policies. According to Porter's theory [70], environmental regulation can promote management innovation and technological innovation. In the process of opening up, enterprises in regions with strict environmental regulations tend to increase green innovation in technologies such as energy conservation and emission reduction, but regions with weak environmental regulations are less affected by policies, resulting in insufficient emission reduction drivers.

To clarify the direction and intensity of various environmental regulations on the green innovation efficiency of enterprises, the

Table 7
Regulatory effect test.

	(1)	(2)
	GTFP	GTFP
treat*post*ML	0.0106*	
	(0.006)	
ML	−0.0125***	
	(0.003)	
treat*post*GZ		0.0115**
		(0.005)
GZ		−0.0068
		(0.004)
treat*post	−0.0014	−0.0743*
	(0.008)	(0.040)
Constant	−0.8521	−1.5308
	(1.730)	(1.735)
Control variables	YES	YES
Observations	23,101	23,101
R-squared	0.369	0.370
Enterprise FE	YES	YES
Year FE	YES	YES

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

effect of environmental regulation was examined. Table 7 presents the regression results of the interaction between command-based environmental regulation and public participation in environmental regulation. The interaction items are significantly positive, indicating that both command-based environmental regulation and public participation in environmental regulation have the potential to strengthen the influence of PFTZ policies on the green innovation efficiency of businesses.

To visually reflect the regulatory effect, the marginal effect of PFTZ policies on the promotion of enterprise green innovation efficiency is plotted (Fig. 4) according to the empirical results in Table 7. As shown in Fig. 4, with stricter environmental regulations, the role of PFTZ policy in improving corporate green innovation efficiency has also become stronger, which also supports the above analysis to a certain extent and verifies the one-way regulation of environmental regulation. However, some of the observations showed less than 0 points, and it is necessary to cross a certain "threshold" to truly improve the extent of the green innovation efficiency of enterprises. Therefore, the results to some extent indicate that the "auxiliary" effect of environmental regulation is not ideal in some areas, and it can help increase the green innovation efficiency of enterprises only when it exceeds a certain threshold.

5.4. Mechanism tests

5.4.1. Cost reduction effect

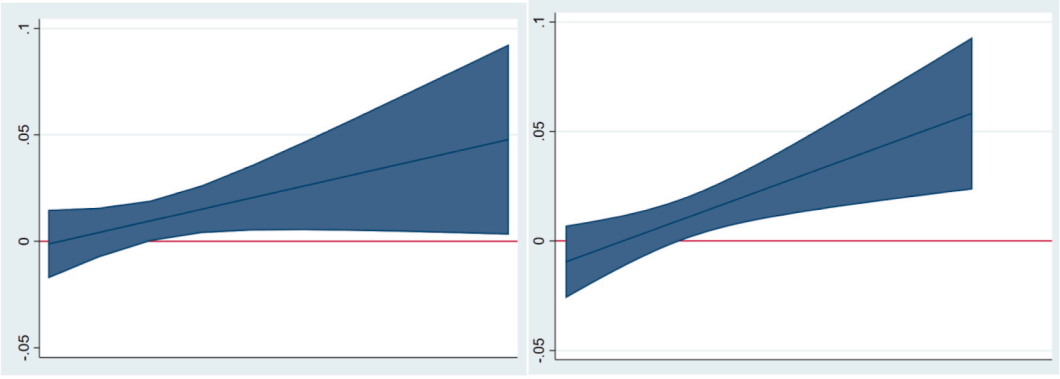
By Costing reduction effect, the establishment of PFTZ can promote green innovation efficiency within businesses. The establishment of PFTZ can broaden financing channels for enterprises and avoid trade barriers to reduce their financing costs. Therefore, enterprises have more funds to participate in green technology transformation and enhance the green innovation efficiency of enterprises. The regression results with the enterprise financing cost as the mediating variable are shown in columns (1) and (2) of Table 8. The results in column (1) show that the establishment of PFTZ effectively reduces the financing cost of enterprises, and the results in column (2) show that the financing cost of enterprises plays a significant mediating effect. This conclusion remains valid after testing. Table 8 Columns (3) and (4) show the regression results with enterprise management cost as the mediating variable, from the results of Column (3), it can be seen that the establishment of PFTZ effectively reduces the management cost of the enterprise, and the results of Column (4) indicate that the enterprise management cost plays a significant mediating effect, and the effect is still valid after the test.

5.4.2. Tax incentive effects

The establishment of PFTZ can promote the green innovation efficiency of enterprises through tax incentives. PFTZ is a special economic zone characterized by tax incentives and special customs supervision with reduced green procurement costs and R&D costs through inclusive tax incentives that provide a guarantee for the green innovation efficiency of enterprises. This zone encourages enterprises to continue conducting experiments in green innovation efficiency. Regression results with tax incentives as the mediating variable are shown in columns (1) through (2) of Table 9. The results of column (1) show that the establishment of PFTZ effectively reduces the effective tax rate paid by enterprises. However, the results of column (2) show that the impact of actual taxation on enterprise green innovation efficiency is not obvious. Therefore, the Sobel test was conducted to confirm the mediation effect, and the results of showed a value of 0.0241, which is less than 0.05. This proves that the tax incentive exerts a significant mediation effect.

5.4.3. Reverse technology spillovers

The establishment of PFTZ will improve the level of enterprise competition and social supervision, promote the continuous improvement of the technological innovation efficiency of enterprises, and improve the efficiency of enterprise resource utilization and green innovation efficiency. The regression results with enterprise innovation as the mediating variable are shown in columns (3) and (4) of Table 9. The results of column (3) indicate that the establishment of PFTZ effectively improves the technological innovation efficiency of enterprises. The results of column (4) show that the technological innovation efficiency of enterprises plays a significant



(a) command-based environmental regulation (b) public participation in environmental regulation

Fig. 4. Marginal impact test of environmental regulation.

Table 8
Mediation effect test I

	(1)	(2)	(3)	(4)
	rz	GTFP	gl	GTFP
treat*post	−0.0114**	0.0094*	−0.0244***	0.0099**
	(0.005)	(0.005)	(0.008)	(0.005)
rz		−0.0166**		
		(0.008)		
gl				−0.0153***
				(0.004)
Constant	0.4262	−2.1008	5.5465***	0.9130***
	(1.835)	(1.709)	(0.176)	(0.108)
Control variables	YES	YES	YES	YES
Observations	20,087	20,087	23,090	23,090
R-squared	0.032	0.368	0.690	0.363
Enterprise FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
Sobel test	0.0003		0.0000	

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

Table 9
Mediation effect test II

	(1)	(2)	(3)	(4)
	js	GTFP	cx	GTFP
treat*post	−0.0683***	0.0139**	0.0444*	0.0099*
	(0.018)	(0.005)	(0.023)	(0.005)
js		−0.0015		
		(0.002)		
cx				0.0061***
				(0.002)
Constant	−0.4053	−2.5240	4.0156***	2.4882
	(6.463)	(1.952)	(0.405)	(1.829)
Control variables	YES	YES	YES	YES
Observations	20,707	20,707	20,996	20,996
R-squared	0.017	0.186	0.348	0.374
Enterprise FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
Sobel test	0.0241		0.0002	

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

mediating effect in the potential of the establishment of PFTZ to improve the green innovation efficiency of enterprises. The P value from Sobel test was less than 0.01, which proves that the reverse technology spillovers exerts a significant mediation effect.

5.5. Further discussion

This paper will further discuss the above empirical results in the context of relevant theories and literature, and provide preliminary interpretation of the above results, to make suggestions for research and practice.

Firstly, the results of the benchmark regression and robustness test in this paper show that the establishment of Pilot Free Trade Zones (FTZs) helps to increase the willingness of enterprises to engage in green innovation and promotes enterprises to continuously improve their own level of green innovation, which is consistent with the existing literature on the environmental benefits of Pilot Free Trade Zones [47,62].

Secondly, the results of the heterogeneity analysis show that (1) the industry-level heterogeneity analysis shows that after the establishment of PFTZ, enterprises in the heavy pollution industry have a stronger motivation to carry out green innovation, and the effect of improving the level of green innovation is more significant, while enterprises in the patent-intensive industry have a higher level of green innovation by virtue of the inherent technological advantages of the issuing body, which is in line with the existing studies [67]; (2) Enterprise-level heterogeneity analysis shows that state-owned enterprises are limited by institutional impacts and have insufficient incentives for green innovation, so the effect of the PFTZ policy on state-owned enterprise green innovation efficiency enhancement is not significant, whereas enterprises with a lower degree of ESG are more motivated to improve the efficiency of enterprises green innovation. This finding has some consistency with the studies of scholars such as Xu Jia [68], Zhang Yang [69], and Drempetic [71].

Thirdly, the results of the moderating effect test show that the control command type environmental regulation and the public participation type environmental regulation all have a facilitating influence on the relationship between PFTZ policy and enterprise

green innovation, which is consistent with Porter's theoretical hypotheses [70], and ensures that this paper's research has a strong theoretical foundation.

Finally, the analysis of the transmission mechanism shows that the establishment of PFTZ improves enterprise green innovation efficiency through the cost reduction effect, tax incentive effect, and reverse technology spillover effect, and the conclusion enriches to a certain extent the research related to the environmental effects of PFTZ and the study on the macro-influencing factors of the green innovation efficiency of enterprises.

Further, the effect of the PFTZ on the green innovation efficiency of enterprises is affected by a wide range of factors, and therefore it is necessary to continue to take active and enhanced policy guidance in order to continuously improve the level of green innovation efficiency of enterprises. The establishment of the PFTZ as an opportunity to promote the realization of sustainable strategic goals not only reflects the requirements for China to achieve high-quality development, but also reflects the rational return of the value orientation of global social development. This study will provide useful policy insights for the further implementation of the opening-up strategy and the promotion of high-quality economic development.

6. Conclusion and policy implications

This study applied a multi-period differences-in-differences model and the ultra-efficient EBM-GML model to measure the green innovation efficiency of domestic listed companies from 2010 to 2021. Moreover, the impact of PFTZ establishment on the technological innovation efficiency of enterprises were empirically tested. According to the results, it is first concluded that the construction of PFTZ significantly improves the green innovation efficiency of enterprises listed in the region. This conclusion is further verified by the results of robustness tests such as measurements with the replacement of the dependent variable, propensity score matching method, placebo test, and removal of the superposition effect of other policies. Second, from the perspective of the transmission mechanism, PFTZ promotes the continuous improvement of the green innovation efficiency of enterprises through the cost reduction effect, tax incentive effect, and reverse technology spillover effect. Thirdly, the heterogeneity analysis revealed significant differences in the effects of PFTZ policies. In particular, PFTZ significantly raises the level of green innovation efficiency of heavily polluting, technology-intensive, and non-state-owned enterprises. Additionally, the impact of PFTZ on the green innovation of businesses becomes even more apparent with the intensification of regional environmental regulation.

Based on the preceding conclusions, the following policy recommendations are put forward:

Firstly, expand the number and scope of PFTZs in China in an orderly manner. At present, 21 PFTZs have been established in China, but the quantity of PFTZs is small in western districts. From the perspective of the geographical location, the western region contains many provinces and borders 13 countries, and border trade is promising for development. In order to build more PFTZs in the future, it is necessary to open up at a high level and build more of them in the western region, which will help the regional economy grow to its full potential. Such an economic growth can be achieved by expanding the scope of PFTZ construction, carrying out deeper and broader institutional reforms, stimulating the endogenous driving force of regional green innovation capabilities and high-quality economic growth, as well as speeding up the construction of a new pattern of development.

Secondly, improve the institutional incentive effect and environmental regulation of energy efficiency, and form a new area of institutional demonstration. The findings of this study show that PFTZ effectively improves the green innovation of enterprises by reducing cost-effectiveness. Moreover, as the intensity of environmental regulatory policies is improved, enterprises are motivated to improve their green innovation. On the one hand, PFTZ should continue to adhere to the concept of ecological priority and green development, and explore green development models with local nature. PFTZs can learn from the green trade system and green finance innovation policies of PFTZs in Shanghai and Tianjin. Full play should be given to the head geese effect of PFTZ, the financing environment of enterprises should be improved, and assistance should be provided to enterprises to carry out environmental governance, energy conservation, and emission reduction. On the other hand, it is necessary to improve the efficiency of law enforcement of PFTZ environmental regulation, accelerate the formation of "Internet + supervision" network supervision, and accelerate the construction of joint supervision, dynamic supervision, and punishment for untrustworthiness. At the same time, it is necessary to focus on the "soft" strength of law enforcement, create a list of exemptions, and improve the regulatory energy efficiency of environmental regulation.

Thirdly, promote a high degree of opening up to the outside world and accelerate innovative applications of ecological environmental science and technology. According to the results of this study, PFTZ can enhance the green innovation level of enterprises through reverse technology spillovers. Therefore, the establishment of PFTZ should take the initiative to benchmark the environmental provisions of international high-standard free trade zones, attract more foreign investment in energy conservation and emission reduction projects, enhance technical learning and interaction between local enterprises and foreign-funded enterprises, and improve the reverse technology spillover effect of PFTZ. In this manner, a new model of coordinated development can be developed for trade and environmental protection. In addition, PFTZ should strengthen the construction of ecological environment informatization and intelligence, promote the intelligent and eco-friendly transformation of the entire procedure, assist PFTZ enterprises in carrying out the transformation of green innovation achievements, increase the initiative and enthusiasm of enterprises in green innovation, and promote the high-quality development of PFTZ economy.

It is noteworthy that despite these contributions, this study has some limitations. Taking PFTZ in China as an example, the effect mechanism of PFTZ on the green innovation of enterprises was empirically tested. However, the findings of this study may not be entirely applicable throughout China considering the vastness of its territories and the wide disparities in economic and cultural status between its regions. In addition, due to the relatively short period of time since the establishment of the FTZs, it is not clear whether the FTZs can sustainably promote the improvement of enterprises' green innovation efficiency in the long run. Therefore, as a next step, it

is necessary to explore the spatial differences in the impact of bonded zones on enterprises' green innovation, and to explore the dynamic and sustained impact of the establishment of bonded zones on enterprises' green innovation efficiency, in order to enrich the empirical evidence of the environmental benefits of bonded zones. Meanwhile, do trade zones bring only the good side of sustainable development? Are the results of the study affected by overlapping benefits? Can the environmental benefits of free zones contribute to net local employment? This is also an important direction for future research.

Funding statement

This study is supported by the Late-stage Subsidy Programme of the National Social Science Foundation of China (22FJLB034) and the Henan Province Higher Education Philosophy and Social Sciences Innovation Talent Support Program (2024-CXRC-15).

Data availability statement

Data on the listed companies considered in this study were acquired from the CSMAR database, the patent data of listed companies were from the China National Intellectual Property Administration, and annual city data were obtained from the "China Urban Statistical Yearbook".

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Guihu Wang: Conceptualization, Funding acquisition, Methodology, Writing – review & editing. **Yirui Hou:** Data curation, Formal analysis, Methodology, Resources, Writing – original draft. **Shanshan Du:** Data curation, Formal analysis. **Chun Shen:** Data curation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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