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Research article

The impact of the free trade zones construction on green technological innovation efficiency ——evidence from 288 cities in Chinese

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ABSTRACT

We measure the green technology innovation efficiency of 288 cities in China from static and dynamic dimensions using the super – SBM model and Malmquist – Luenberger index, and employ "Difference in Difference" (DID) model to evaluate the impact of FTZs construction on green technology innovation efficiency using panel data from 288 prefecture-level cities from 2008 to 2020. The findings show: (1) The FTZs significantly improve green technology innovation efficiency. The decomposition indexes promote the green technology innovation efficiency more from the dynamic productivity dimension (GTFP) functioning on technological advancement. (2) The FTZs can boost the efficiency of green technology innovation through industrial agglomeration, digital economy, and government financial support; (3) The effect of FTZs on the efficiency of green technology innovation differs based on the size and location of the city. Green technology innovation will reach maximum potential when promoting FTZ policy in less developed central, western, and interior regions. This study addresses whether FTZ policies can genuinely support regional green innovation and policy insights to expand opening up and enhance high-quality economic growth.

1. Introduction

Free Trade Zones (FTZs) have gained popularity among governments seeking to attract foreign investment, increase trade, and generate innovation. With increasing concern about climate change and environmental degradation, there is an increasing interest about the potential impact of FTZs on the development of green technologies. China's pilot free trade zones have expanded to 21 provinces by the end of 2022, forming a strategic framework from China's coast to its center to its west. The relationship between the FTZs and eco-innovation of is one of the most pressing issues [1]. The FTZs may increase the environmental burden and cause ecological damage. Grossman et al. (1991) used the NAFTA context to determine that foreign inflows from FTZs exacerbated atmospheric pollution in Mexico while contributing to the country's economic development [2]. Other developing regions experienced similar outcomes [3,4]. Alternatively, free trade may also enhance environmental quality. Antweiler et al. (2001) conclude that FTZs may be more advantageous for green innovation after discussing structural, scale, and technology effects [5]. Despite the ongoing

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controversy regarding the relationship between international trade and environmental quality, few studies have conducted an in-depth analysis of the relationship between FTZs and the efficacy of green technology innovation.

In this study, our primary objective is to explore the intricate relationship between Free Trade Zones (FTZs) and the efficiency of green technology innovation, particularly within the context of China's rapidly expanding FTZs. Recognizing the growing popularity of FTZs among governments for attracting foreign investment, increasing trade, and fostering innovation, we aim to delve into the dual nature of FTZs: their potential to both exacerbate environmental challenges and contribute to the advancement of green technologies. The problems we investigate stem from a critical and timely concern: while FTZs are hailed for their role in boosting trade and investment, their environmental implications remain a contentious and underexplored area. Our study specifically addresses the problem of balancing economic development with environmental sustainability in the context of FTZs. This is a pressing issue as the rapid expansion of FTZs, particularly in developing countries like China, raises questions about their potential environmental impact. While FTZs can drive economic growth, their operations often lead to increased environmental burdens, such as heightened pollution levels and resource depletion, as evidenced by Grossman et al. (1991) in the context of NAFTA [2]. This juxtaposition creates a significant challenge: how can FTZs continue to be engines of economic growth without compromising environmental sustainability?

Green and innovation are significant factors in promoting the economy's transition from high-speed growth to high-quality development and realizing the synergistic development of economic society and ecological civilization; the construction of FTZs can promote the foreign investment system and absorb advanced foreign technologies [1]. In this study, our primary objective is to explore the intricate relationship between Free Trade Zones (FTZs) and the efficiency of green technology innovation, particularly within the context of China's rapidly expanding FTZs. Recognizing the growing popularity of FTZs among governments for attracting foreign investment, increasing trade, and fostering innovation, we aim to delve into the dual nature of FTZs: their potential to both exacerbate environmental challenges and contribute to the advancement of green technologies.According to BP's World Energy Statistical Yearbook, China's CO2 emissions rose from 7.71 billion tons in 2009 to 9.899 billion tons in 2020, leading globally with an average annual growth of 2.30%. This highlights the pressing challenge China faces in combating climate change and reducing greenhouse emissions. In this context, the role of green technology innovation is increasingly vital.Recent studies suggest significant policy influence on green innovation. Yang et al. (2023) found that green finance policies effectively reduce environmental pollution in specific regions using a difference-in-differences approach [6]. The finding reinforce the notion that effective policy-making is crucial in fostering green technological innovation.

Therefore, our research aims to fill this gap by providing an in-depth analysis of the efficiency of green technology innovation within FTZs. We seek to clarify whether and how FTZs can contribute to sustainable economic development while mitigating their environmental impact. This investigation is crucial for policymakers and stakeholders involved in the development and management of FTZs, as it will inform strategies that align economic growth with environmental sustainability. By considering environmental benefits in addition to economic and social gains, we measured the green technology innovation efficiency. From the static efficiency, we employ the super – SBM model with undesirable outputs to assess the green technology innovation efficiency. From the dynamic productivity dimension, we use the Malmquist – Luenberger index model and the frontier jointly constructed by all stages as the reference frontier to asses the green total factor productivity variation index (GML) and its decomposition indicators, including the change index of technical efficiency (GEC), and the change index of technological progress (GTC). This study directly responds to the central question of whether FTZ policy can genuinely promote the efficiency of green technology innovation, investigates the FTZ's potential environmental benefits, and offers theoretical and empirical guidance for the continued development of the FTZs.

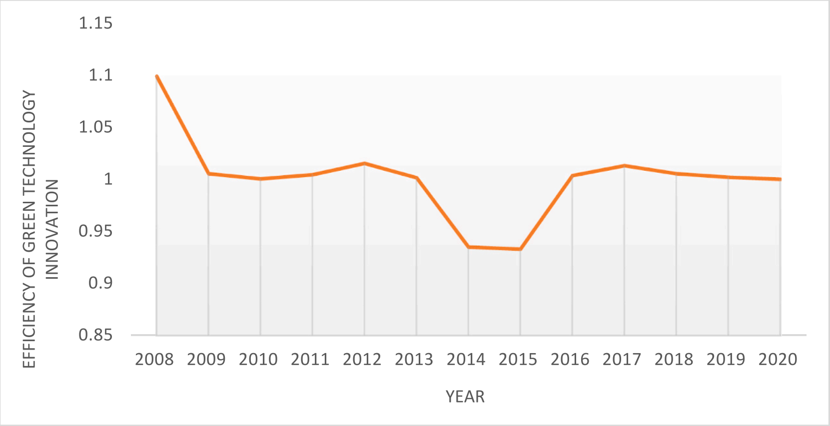


Fig. 1. Variations of innovation in green technology efficiency from 2008 to 2020.

2. Theoretical analysis

2.1. 1The direct impact of FTZs on green technology innovation efficiency

The direct impact of Free Trade Zones (FTZs) on green technology innovation efficiency is analyzed through the lens of the traditional administrative system and the innovation environment. These aspects have been historically associated with inefficient factor allocation and low R&D activities, which are central to the discourse on green technology innovation centered around the green development concept. As experimental areas of institutional innovation, FTZs carry a multidisciplinary and multilevel innovation mission, impacting trade, investment, and finance. Measures such as trade and investment facilitation, financial innovation, and opening-up reforms within FTZs enhance the external economic environment for business innovation, providing a conducive policy framework for productive service industries, high-tech industries, and innovation capital within FTZs. These factors collectively contribute to reducing the cost of green technology innovation and optimizing the environment for enterprise-level green technology innovation. Fig. 1 demonstrates that since 2015, when the FTZs construction has been vigorously promoted, the efficiency of green technology innovation in the region has increased significantly.

In this process, the transformation of government services, investment, and trade facilitation, a significant aspect of the development of FTZs, broadens access to the outside world to enhance green technology innovation activities even further. The initial action is to reorganize government functions. The supervision system will be strengthened due to government simplification, decentralization, and optimization of reform services, promoting the transition from a management-oriented to a service-oriented government and maximizing the market's decisive role in resource allocation. A series of one-of-a-kind systems, such as "negative list," "single window," and "first enter the zone, then declare," significantly reduce enterprise transaction and production costs, increase factor allocation efficiency, and consequently reduce the cost of research and development for innovative activities. Moreover, a market-oriented competitive environment provides more incentives for R&D activities and enhances the effectiveness of green technology innovation efforts [7].

The second concern is investment and commerce facilitation. Foreign investment is attracted to the region by lowering investment entry barriers and trade and investment facilitation reforms, along with the entry of advanced technology and management experience, and the difference between domestic and foreign enterprises motivates local enterprises to increase R&D investment; the liberal and open trade environment promotes the free flow of goods and factors and the expansion of trade [8]. Due to the cost and technological advantages, foreign goods crowd out local goods, encouraging local businesses to produce more competitive products and thereby increase market competitiveness. The intensification of market competition increases the efficiency of green technology innovation directly.

They are third, expanding the entrance to the outside world. Increasing openness to the outside world enables businesses to obtain the benefits of the technology spillover effect, enterprise cooperation, and the increasingly common free movement of talents. The elements of high technology aptitude serve as a foundation for innovation activities in green technology. Enterprises learn, assimilate, and replicate the international technological frontier through technology introduction and cooperation, resulting in secondary technology innovation [2]. The "imitation learning effect" reduces innovation expenses, increasing the efficiency of green technology innovation. Thus, we propose hypothesis H0.

Hypothesis H0. The FTZs construction can boost the green technology innovation efficiency.

2.2. The indirect impact mechanism of FTZs on green technology innovation efficiency

2.2.1. Industrial agglomeration

The degree of industrial agglomeration strongly correlates with firms' innovative R&D activities [9], serving as a potent incentive for businesses to pursue innovative R&D. The spillover, scale, and competition effects of industrial agglomeration can increase the effectiveness of green technology innovation. Consider the spillover effect first. As an unintentional disruption, establishing an FTZ upsets a region's original equilibrium, causing production components to congregate in the FTZ, fostering the development of specialized production and services, and eventually forming a concentrated market [10]. Industrial agglomeration can increase intra- and inter-industry knowledge diffusion and technology dissemination, resulting in technological advancement. High-end firms with similar products, manufacturing processes, internal technologies, and green innovation resources are located in the region, creating a shared market for high-end elements and permitting diverse divisions of labor and cooperation. The inquiry and learning costs for green innovation knowledge and information decrease gradually. Through "learning by doing" effect, the diffusion of innovation is accelerated, increasing the overall level of green technology innovation in the region.

The scale effect is the second effect. Under the direction of the FTZ policy, the concentration of production factors in the zone leads to market expansion and the continuous expansion of companies' production scale. Moreover, enterprise technological innovation activities and scale exhibit a positive correlation, and the impact of economies of scale can enhance the technological innovation capability of businesses [11]. The economy of scale effect decreases the production cost of intermediate goods for enterprises, increases the supply of intermediate products, and improves the quality of intermediate products in the zone, thereby assisting forward and backward-associated enterprises in enhancing their production efficiency, driving the efficiency of R&D personnel, R&D funds, and other factor inputs and outputs, and promoting the efficiency of green technological innovation.

The third factor is the effect of competition. Porter (1990) argues that the geographical concentration of firms within an industry cluster creates a competitive advantage by developing a collaborative outcome [12]. The limited scope of FTZs and market-driven mechanisms enhance the competitive advantage of upstream and downstream industrial concentration. Associated enterprises outside FTZs tend to improve the efficiency of enterprise technological innovation to enter FTZs to obtain more institutional dividends; consequently, firms inside and outside the zones will compete to increase R&D investments in green technological innovation and improve production efficiency. Thus, we propose the following hypothesis.

Hypothesis H1. The FTZs can enhance green technology innovation efficiency through industrial agglomeration.

2.2.2. *Digital economy*

Digital elements have become the new elements driving economic transformation and development, which can increase the speed of information transmission, decrease data processing and transaction costs, and optimize resource allocation [13]. By lowering R&D costs, upgrading industrial structure, and optimizing the market environment, the growth of the digital economy in FTZs can further impact the efficiency of green technological innovation.

Initially, it reduces R&D expenditures. Digital information and knowledge are essential components of the digital economy. Their virtual, highly mobile, and non-competitive characteristics ensure that digital elements are not limited by geographic space in the dissemination process and can be quickly accessed and utilized, thereby effectively reducing market information asymmetry and information distortion as well as the mismatch between supply and demand in green technology research and development, process, and product. Unlike conventional production factors, the digital economy's information value does not preclude using other subjects. Consolidating elements utilized in the production and consumption process can further expand the data and data value scale, which has a powerful demonstration effect on other businesses in the region and encourages more companies to implement digital reform. The scale economy of digital elements increases the degree of green technological innovation by enhancing the spillover effect of advanced technological innovation and company management expertise.

Second, it encourages industrial structure modernization. The diversity of various sectors in the innovation process, investment requirements, and knowledge base will influence the innovation performance of businesses [14]. The digital economy may contribute to enhancing the efficiency of the green economy, and both industrial digitization and digital industrialization stimulate the development of green economy efficiency. From the perspective of industrial digitization, traditional industries with low industrial levels and high pollution emissions can achieve high integration and synergistic interaction in the production supply chain, reduce enterprise production and operation costs, improve the efficiency of enterprise green technology innovation, and strengthen enterprise core competitiveness through digital transformation in production and operation fields such as product and service. Digital industrialization provides mature digital technology, products, services, infrastructure, and solutions for the industry's digital development, deepens the industry's digital reform, leads to consumer demand transformation toward digitalization, and enhances green technology innovation capability.

Thirdly, it improve the market's conditions. The digital economy transforms enterprise pollution monitoring and green technology evaluation systems, enhancing environmental supervision and optimizing market conditions. The FTZs investigates the development of digital government and establishes a digitally integrated supervision and service platform to facilitate the digitally facilitated sharing of management information among market entities. Informatization and digital reform based on networking data make the market open and transparent. The government can monitor the degree of green production and data pollutant emission level of enterprises via platforms such as enterprise monitoring and force enterprises to green transformation based on green and low-carbon policy orientation, increase enterprise willingness to green technology innovation, and enhance the effectiveness of green technology innovation. Consequently, we propose the following hypothesis.

Hypothesis H2. The FTZs can increase green technology innovation efficiency through digital economy.

2.2.3. *Government financial support*

Government programs that support science and technology innovation can mitigate the risks associated with technological innovation while boosting the technical innovation potential of businesses [15].

First, concerning direct government support, the externality characteristics of green technology innovation result in a positive "crowding-in effect" and a negative "crowding-out effect" of government science and technology expenditure on firms' green technology innovation. Government spending on science and technology, according to the "crowding-in effect," is a reallocation of research and innovation resources that determines the pace and direction of technological innovation [16] and has a "leading effect" and demonstration role [17]. Under solid fiscal policy guidance, social capital flows preferentially to government-supported enterprises with high levels of technological innovation. Diversified financing is made possible, effectively relieving the financing constraints of SMEs and boosting their confidence in green transformation. According to the "crowding out effect," government spending on science and technology raises the market price of factors and increases the cost of R&D, reducing enterprises' R&D investment in green technology innovation. Moreover, the contradiction between local governments' short-term performance assessment mechanism and long-term technology innovation causes enterprises to improve their technology level through technological innovation in the short term and reduce the margin of survival for green technology innovation R&D companies. The FTZ policy permits trial and error. The fault-tolerant innovation mechanism allows mistakes and deviations in innovation activities, thereby altering the traditional means of local government performance evaluation and effectively mitigating the "crowding-out effect" of government support for science and technology. In contrast, the "crowding-in effect" predominates.

Second, in the term of indirect government assist, in addition to direct government spending on science and technology, such as R&D subsidies and tax incentives, government support in the FTZs is also reflected in indirect support, such as the opening up of financial services and the development of innovative financial products and services that effectively reduce the financing costs of enterprises. Green finance has become an integral component of the innovation of financial activities in the FTZ to support further economic activities for environmental development, climate change, and resource efficiency. For instance, the eleventh cohort of financial innovation cases in Shanghai FTZ contains five green finance innovation cases. The policy support for green finance in the FTZ has resulted in the concentration of funds in energy-saving and environmental protection enterprises, reducing the financial pressure on enterprises to engage in green technological innovation activities and contributing to the enhancement of the efficiency of green technological innovation. Thus, we propose the following hypothesis.

Hypothesis H3. The FTZs can boost green technology innovation efficiency through Government financial support.

3. Research method

One of the primary objectives of this research is to scientifically assess the impact of the establishment of Free Trade Zones (FTZs) on the efficiency of green technology innovation. To disentangle the temporal effects from policy impacts, we have adopted the Difference in Differences (DID) model as our main research method. This approach involves treating cities within the FTZs as the treatment group and cities outside the zones as the control group. We assume that prior to the establishment of the FTZs, the trends in green technology innovation efficiency for both groups were broadly similar. Any differential changes observed between the two groups post-establishment are attributed to the policy effect. This refined approach ensures that our hypotheses are directly in line with the objectives of the study, providing a clear link between our methodological choices and the anticipated outcomes. Theoretically, we have expanded the discussion on the contribution of our findings to the body of knowledge on green technology innovation efficiency, aligning with the super-SBM model and Malmquist-Luenberger index. Empirically, the study's analytical rigor has been fortified through the employment of MAXDEA Ultra software for data envelopment analysis and Stata 16.0 software for regression analysis, ensuring precise and reliable outcomes. Furthermore, we have underscored the managerial implications by articulating actionable insights for urban planners and policymakers, which are instrumental in promoting green technology innovation within Free Trade Zones (FTZs) and advancing sustainable urban development strategies.

3.1. Model specifications

3.1.1. Baseline model

China has successfully establish 21 FTZs since establishing the Shanghai FTZ in 2013, both in less-developed interior regions and developed coastal areas. Assuming that the impact of FTZs construction on the green technology innovation efficiency will only affect provinces and cities that have been approved to build FTZs. Regions and cities approved to construct FTZs serve as treatment groups, while other provinces that have not been permitted to construct FTZs help as control groups. By comparing and evaluating the differences between the treatment and control groups, it is possible to assess the impact of FTZ establishment on green energy performance. We examine the impact of the pilot FTZ policy on the green technology innovation efficiency innovation using the "Difference in Difference" (DID) model, as described by equation (1).

$$Y_{it} = \alpha_0 + \alpha_1 \mathrm{Treat}_i{*}\mathrm{Time}_t + \gamma X_{it} + f_i + f_t + \varepsilon_{it} \tag{1}$$

Where Y_{it} is the performance of the area's green technology innovation efficiency over the period. i represents regions and t denotes year. The regional dummy variable Treat_i is used to identify if a region i is located in a province or city where the FTZ is to be built, and Time_t is the time dummy variable used to decide whether the permission for the erection of a FTZ. The interaction term $\mathrm{Treat}_i{*}\mathrm{Time}_t$ between the regional dummy variable Treat_i and time dummy variable Time_t reflects the FTZ policy. The coefficient and significance of the policy variable are crucial factors for determining if the creation of FTZs affects green technology innovation efficiency. X_{it} is the set of control variables, f_i is the regional fixed effect, f_t is the time fixed effect, ε_{it} is the random error term, and α_0, α_1, γ are the parameters to be estimated. The coefficient α_1 is the focal point. If the coefficient r is considered positive, it suggests that introducing FTZs has boosted green technology innovation efficiency.

3.1.2. parallel trend test model

Whether the DID regression results are practically meaningful depends on whether the parallel trend hypothesis is satisfied prior to policy implementation. As a result, equation (2) was developed to perform the parallel trend test for panel data to assess the dependability of classic DID regression results.

$$y_{i,t} = \beta_0 + \sum_{k=-n}^{m} \beta_k D_{i,t_0+k} + X'\rho + \mu_i + \upsilon_t + \varepsilon_{it} \tag{2}$$

where: $D_{i,t_{0+k}}$ is a series of dummy variables, t_0 represents the time when the urban i policy experiment started; $m > 0$ and $n > 0$; $t_0 + k$ represents the year k before or after the policy experiment; β_k coefficient represents the difference in the trend of the dependent variable between the experimental and control group cities in the year k before (after) the policy experiment, indicating the difference in the trend of green technology innovation efficiency; X is a series of control variables. The essence of the event study method is to investigate differences in the trends of dependent variable between city i and its control group cities from year n before the policy experiment to year m after the policy experiment. Consequently, the key to the parallel trend test is matching the estimated effects to the corresponding control and experimental groups and subsequently examining trends over the time window.

3.2. Variables

3.2.1. Measurement of green technology innovation efficiency

In light of the connotation of green technological innovation, we consider environmental benefits in addition to economic and social benefits. Actual GDP and patent output are desirable outputs, while industrial wastewater, industrial sulfur dioxide, and industrial smoke (powder) dust emissions are undesirable outputs. Based on the industrial proportion statistics, the missing values are correctly updated (unit: 10000 tons). We assess the efficiency of green technology innovation along the lines of static efficiency and dynamic total factor productivity.

On the one aspect, regarding static efficiency, Tone (2003) suggested a non-radial and non-angular SBM model to address the issue of insufficient input or non-relaxation and handle the efficiency assessment with undesirable outputs [18]. Based on prior research, we employ the super − SBM model with undesirable outputs to assess the performance of different prefecture-level cities and cities above in China from 2008 to 2020 regarding green technology innovation noted as GIE.

equation (3) is the definition of the SBM model's production possibility set concerning undesirable outputs:

$$P=\{(x,y,b)|x\geq X\zeta, y\leq Y\zeta, b\geq B\zeta, \zeta\geq 0\} \tag{3}$$

Where , $\sum_i^m\zeta=1, x\in R^{m\times n}, y\in R^{S_1\times n}, b\in R^{S_2\times n}$, the matrix $x=[x_1,\dots,x_n]\in R^{m\times n}, y=[y_1,\dots,y_n]\in R^{s_1\times n}, b=[b_1,\dots,b_n]\in R^{s_2\times n}, s=s_1+s_2$ represents s outputs.

The SBM model with undesirable outputs is represented by equation (4):

$$\gamma^*=\min\frac{1-\frac{1}{m}\sum_i^m\frac{s_i^-}{x_{i0}}}{1+\frac{1}{s_1+s_2}\left[\sum_{r=1}^{s_1}\frac{s_r^y}{y_{r0}^a}+\sum_{r=1}^{s_2}\frac{s_r^b}{b_{r0}}\right]} \tag{4}$$

$$\text{s.t.}\begin{cases} x_0=X\zeta+s^- \\ y_0=Y\zeta-s^y \\ b_0=b\zeta+s^b \\ s^-\geq 0, s^y\geq 0, s^b\geq 0 \end{cases}$$

Where s^-、s^a and s^b are the relaxation of inputs, desirable outputs, and undesirable outputs. ζ is the weight, and r^* is the output efficiency.

On the other, from the dynamic productivity dimension, using the Malmquist – Luenberger index (referred to as the ML index) model and the frontier jointly constructed by all stages as the reference frontier, the green total factor productivity variation index (GML) and its decomposition indicators, the change index of technical efficiency (GEC), and the change index of technological progress (GTC), for each prefecture-level city and above. Specifically, the directional distance function, which handles desirable and undesirable outputs in a given direction asymmetrically, is formalized in equation (5).

$$\underset{D}{\rightarrow}(x,y,b;g)=\sup\{\beta:(y,b)+\beta\quad g\in p(x)\} \tag{5}$$

Where $g=(y,-b)$ represents the output change direction vector, i.e., the direction in which expected output grows and undesirable output drops, β represents the directional distance function value, and $p(x)$ represents the production possibility set.

By merging the global production potential set of n and n+1 periods to create an ML index to quantify green total factor productivity, the ML index can be represented as equation (6):

$$ML=\left[\frac{1+{}_{D}^{r}\,{}_{0}^{n+1}(x^n,y^n,b^n,-b^n)}{1+{}_{D}^{r}\,{}_{0}^{n+1}\left(x^{n+1},y^{n+1},b^{n+1},-b^{n+1}\right)}\times\frac{1+D\,{}_{D}^{r}\,{}_{0}^{n+1}(x^n,y^n,b^n;y^n,-b^n)}{1+{}_{D}^{r}\,{}_{0}^{n+1}\left(x^{n+1},y^{n+1},b^{n+1};y^{n+1},-b^{n+1}\right)}\right]^{1/2} \tag{6}$$

Table 1
Input-Output Indicators and Descriptions for Measuring the green technology innovation efficiency.

First grade indicators	Second grade indicators	Indicator description
Input index	Labor force input	Total social employment at the end of the year (unit: 10000 people)
	Capital investment	Capital stock estimated by the perpetual inventory method(unit: 100 million CNY)
	Energy input	total social electricity consumption (unit: 100 million kW/h)
Desirable outputs	Economic output	Real GDP (unit: 100 million CNY)
	patent output	Number of patent applications
Undesirable outputs	Three industrial waste	Industrial wastewater discharge (unit: 10000 tons)
		Industrial sulfur dioxide emissions (unit: ton)
		Industrial smoke (powder) dust emissions (unit: ton)

Where b^n and b^{n+1} denote the undesirable outputs of the decision-making unit in the n and n + 1 periods, respectively.

Since the GML index refers to the rate of change in current-year productivity relative to the previous-year output rate rather than productivity itself. As a result, we assume that the TFP for 2008 is 1. The TFP for 2008 is multiplied by the GML productivity index for 2009, and the TFP for 2010 is multiplied by the GML productivity index for 2010. By comparison, we may calculate the green technology innovation efficiency (GTFP) for each prefecture-level city and above from 2008 to 2020. The calculation procedures for GEC and GTC are the same as those for GTFP. Table 1 shows the specific input-output indications (see Table 2).

3.2.2. Dependent variable

The construction of FTZs can be thought of as a "policy shock," and whether or not a FTZ has been established in a city as the dependent variable in this study. In model (1), $Treat_i$ is the Dummy variable that differentiates the treatment group from the control group, with $Treat_i = 1$ for the treatment group (cities inside the province (city) where founded FTZ) and $Treat_i = 0$ for the control group (cities where is not established the FTZ). $Time_t$ is the FTZ policy period's dummy variable. If a FTZ is founded in a region during a specific year, $Time_t = 1$ for the year following the founded of the FTZs and $Time_t = 0$ for the year preceding the foundation of the FTZs. In this study, the interaction term $Treat_i{*}Time_t$ indicates the net effect of the FTZs construction, so the coefficient α_1 of the interaction term is the focus, and if α_1 is significantly positive, it means that the FTZ establishment has played a significant role in promoting green technology innovation efficiency.

3.2.3. Control variables

In addition to policy issues, economic development level, human capital, information technology degree, transportation infrastructure, and government participation in the economy may impact green technology innovation. As a consequence, we introduce these elements as control variables with the following particular measurement methods.

(1) Economic development level (Pgdp): GDP per capita is used to calculate the regional economic development level, with 2007 as the base year to account for the effect of pricing considerations.
(2) Foreign direct investment level (Fdi): the actual amount of foreign direct investment used in the region as a percentage of GDP.
(3) Informatization level (Inf): the ratio of mobile phone users to the region's resident population.
(4) Human capital (Hc): the ratio of students enrolled in general higher education schools to the resident population in the region.
(5) Transportation infrastructure (Tran): the ratio of road density (the ratio of road miles to the total area of the region).
(6) Government financial support (Gov): the ratio of total government financial spending to GDP.

3.3. Data Sources and descriptive statistics

There are now 20 FTZs and one free trade port in China. However, only three inland FTZs are in the western area, including Sichuan, Chongqing, and Shanxi. Given the shifts in the economic situation and environmental protection situation around 2008, we evaluate the impact of FTZs construction on the green technology innovation efficiency using panel data from 288 prefecture-level from 2008 to 2020. Except for data on applied and granted patents collected from the State Patent and Intellectual Property Office (SIPO), the original data are from provincial and city statistics yearbooks and statistical bulletins. Table 1 shows the descriptive statistics for the relevant variables.

4. Results and analysis

4.1. The impact of the FTZ implementation on green technology innovation

To test the net effect of FTZ establishment on the green technology innovation efficiency, we introduced a series of control variables while controlling for time-fixed and city-fixed effects. Table 3 shows the setup of free trade zones can considerably boost green technology innovation in cities. More specifically, the impact of FTZ creation on green total factor productivity (GTFP) in the dynamic

Table 2
Descriptive statistics of variables.

Variables	Observations	Mean	Std. Dev	Min	Max
Gie	3744	0.3078	0.1665	0.0659	1.5670
Gtfp	3744	0.6193	0.2031	0.1335	2.2754
Gec	3744	0.8774	0.2265	0.1757	3.6077
Gtc	3744	0.7093	0.1887	0.2315	4.1853
*Treat*Time*	3744	0.1896	0.3921	0	1.0000
Pgdp	3744	0.6883	0.5648	−1.1136	2.2934
Fdi	3744	0.0290	0.0330	0	0.4262
Hc	3744	0.0167	0.0197	0	0.1276
Inf	3744	0.9176	0.3641	0.0510	3.1330
Tran	3744	1.0547	0.5026	0.0476	2.6279
Gov	3744	0.1983	0.1065	0.0426	1.0268

Table 3
The impact of the FTZ implementation on green technology innovation.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Gie	*Gie*	*Gtfp*	*Gtfp*	*Gec*	*Gec*	*Gtc*	*Gtc*
Pol	0.0129***	0.0099**	0.0464***	0.0412***	0.0234***	0.0140*	0.0520***	0.0526***
	(0.0044)	(0.0042)	(0.0064)	(0.0059)	(0.0090)	(0.0084)	(0.0070)	(0.0071)
Pgdp		0.1624***		0.2318***		0.3721***		0.0006
		(0.0095)		(0.0134)		(0.0189)		(0.0160)
Fdi		−0.0559		−0.0967		−0.2760***		0.1866**
		(0.0530)		(0.0747)		(0.1058)		(0.0894)
Hc		0.2615		0.2975		1.0414*		−0.1131
		(0.2898)		(0.4082)		(0.5786)		(0.4889)
Inf		−0.0048		0.0151		0.0014		0.0137
		(0.0084)		(0.0119)		(0.0168)		(0.0142)
Tran		−0.0589***		−0.0821***		−0.0703***		−0.0107
		(0.0106)		(0.0149)		(0.0212)		(0.0179)
Gov		−0.1513***		−0.4817***		−0.4001***		−0.2328***
		(0.0313)		(0.0441)		(0.0625)		(0.0528)
Cons	0.4989***	0.4780***	1.0000***	0.9976***	1.0000***	0.8920***	1.0000***	1.0341***
	(0.0039)	(0.0136)	(0.0057)	(0.0192)	(0.0080)	(0.0272)	(0.0063)	(0.0230)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3744	3744	3744	3744	3744	3744	3744	3744
cities	288	288	288	288	288	288	288	288
R^2	0.5136	0.5690	0.6731	0.7251	0.3417	0.4406	0.4800	0.4841

Note: ***, ** and * represent significance levels of 1%, 5%, and 10%, respectively. Clustering robustness standard errors are shown in parentheses.

productivity dimension is more substantial than that of GIE in the static efficiency dimension. Further, the positive effect of the policy shock of FTZ establishment on the index of technological progress change (Gtc) (0.526) is significantly more significant than that on the index of technical efficiency change (Gec) (0.14). They both pass the 1% significance level test, indicating that establishing FTZs contributes more to improving GTFP by acting on technological progress and boosting the effectiveness of green technology innovation. The regression results substantiate the Hypothesis H0: The FTZs construction can boost the green technology innovation efficiency.

4.2. Parallel trend test

Fig. 2 illustrates the results of the parallel trend, where −5 represents the parallel trend difference of green technology innovation efficiency between FTZ cities and control group cities in the fifth year prior to policy implementation, −4, −3, −2, and −1 have similar

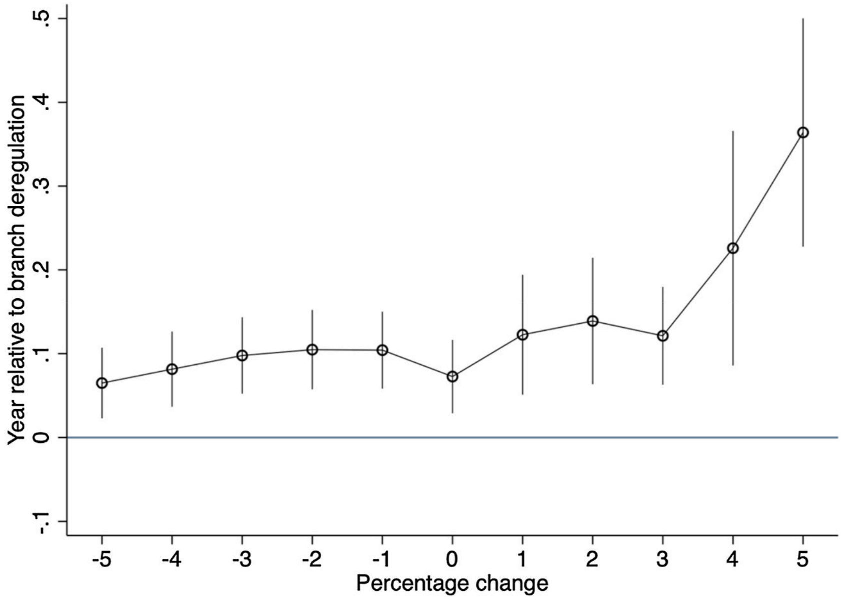


Fig. 2. Parallel trend test result.

meanings, and 0 represents the current period of FTZ policy implementation. During the event period preceding the implementation of the FTZ policy, there was no significant difference between the treatment group and control group cities' green technology innovation efficiency. Furthermore, following the implementation of the FTZ policy, the green technology innovation efficiency of the cities in the treatment group improved significantly, with the improvement becoming more pronounced over time. Consequently, the results of the initial DID can be considered practically relevant.

4.3. Robustness tests

4.3.1. Results with alternative measures of independent variable

We first perform a robustness test using the approach of altering measures of green technology innovation. To begin, as an alternative indication of green technology innovation efficiency, use the logarithmic value of the number of green invention patents applied (Gupa) and the number of allowed green invention patents that lag for one period (Gipa). The subsequent action is to consider the undesirable output in the process of green technology innovation, choosing the "three wastes" (tons/100 million yuan) discharged per unit of industrial added value as the undesired output, calculating the weight using the entropy approach, and establishing a comprehensive index. The poorer the green technology innovation efficiency, the higher the index. The reciprocal processing (Wdi) is used as an alternate indicator of green technology innovation efficiency to facilitate measurement. Table 4 shows the results. After adjusting for the factors above, the favorable effect of FTZs construction on green technology innovation persists.

4.3.2. Alter estimating method

We use the PSM-DID estimation approach to evaluate the robustness of the baseline regression results. First, we selected variables like information technology and foreign direct investment to perform neighborhood matching on data from the treatment and control groups. Fig. 3 (a, b) show the kernel density distribution of the propensity scores of the two groups of samples before and after matching. The average propensity matching score of the control group is considerably lower than that of the treatment group before matching, as described in Fig. 3 (a). Following matching, the probability distributions of the two sets of samples tend to be consistent, demonstrating that using propensity matching may effectively reduce the samples' selective bias. Then we ran a balancing test on the covariates of the two sets of samples. The results indicated that the mean difference between the matched covariates was less than 0.1, as represented in Fig. 3 (b), suggesting no significant systemic difference between the treatment and control groups. Finally, utilizing the matched sample data of 14 cities (including seven control groups and seven treatment groups), we tested the effect of FTZ construction on green technology innovation. Table 5 displays the regression findings. The study's results remain valid after modifying the estimating procedure.

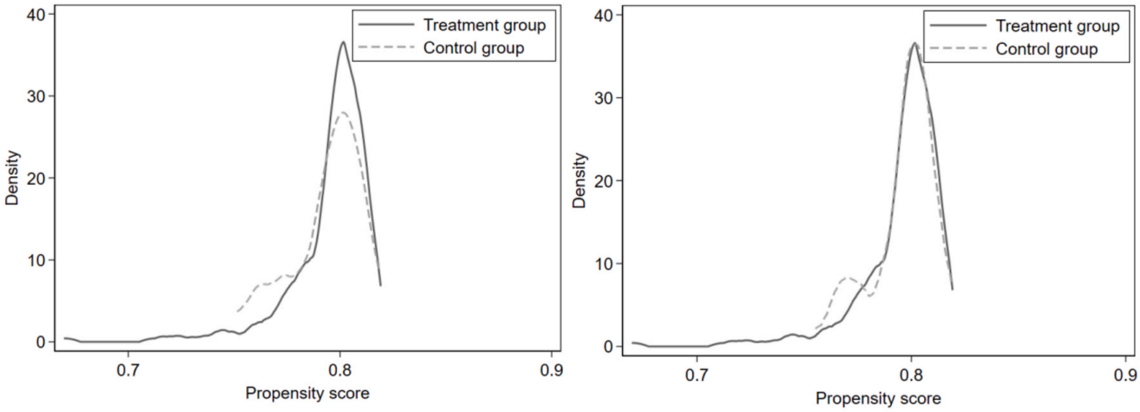
4.3.3. Replace the treatment group and the control group

To emphasize the convergence between the treatment and control groups, we examined whether the empirical results changed when the treatment and control groups altered. Cities enrolled in the FTZs are now classified as the treatment group, while others are categorized as the control group. The robustness test was investigated in 229 cities, 48 of which were in the treatment group and 181 in

Table 4
Regression results of independent variable substitution.

Variables	(1)	(2)	(3)
	Gupa	*Gipa*	*Wdi*
Pol	0.0238***	0.0039***	3.9926**
	(0.0036)	(0.0014)	(1.9116)
Pgdp	−0.0187**	0.0019	38.3199***
	(0.0081)	(0.0033)	(4.3167)
Fdi	0.0330	0.0401**	123.3812***
	(0.0454)	(0.0176)	(24.1060)
Hc	−0.3959	−0.2547***	−67.9442
	(0.2481)	(0.0982)	(131.8115)
Inf	−0.0426***	0.0088***	−13.1875***
	(0.0072)	(0.0028)	(3.8294)
Tran	−0.0839***	−0.0164***	−2.9212
	(0.0091)	(0.0038)	(4.8244)
Gov	−0.2094***	−0.0510***	9.7684
	(0.0268)	(0.0107)	(14.2416)
Cons	0.1507***	0.0214***	26.3642***
	(0.0116)	(0.0048)	(6.1899)
Year FE	Yes	Yes	Yes
City FE	Yes	Yes	Yes
Observations	3744	3744	3744
cities	288	288	288
R^2	0.2329	0.0993	0.1916

Note: ***, ** and * represent significance levels of 1%, 5%, and 10%, respectively. Clustering robustness standard errors are shown in parentheses.



(a) Prior to matching

(b) After matching

Fig. 3. Kernel density distribution of propensity scores in the treatment and control groups before and after matching.

Table 5
PSM-DID estimation results.

Variables	(1)	(2)	(3)	(4)
	Gie	*Gie*	*Gtfp*	*Gtfp*
Pol	0.0799**	0.0758**	0.1054***	0.1060***
	(0.0323)	(0.0300)	(0.0355)	(0.0332)
Pgdp		0.5309***		0.4530***
		(0.0782)		(0.0866)
Fdi		−0.2878		−0.1089
		(0.4344)		(0.4811)
Hc		1.1191		2.4119**
		(0.9912)		(1.0977)
Inf		0.0354		0.1131*
		(0.0554)		(0.0614)
Tran		0.1111		0.0803
		(0.1117)		(0.1237)
Gov		0.1666		−0.0148
		(0.1542)		(0.1708)
Cons	0.5044***	−0.1442	1.0000***	0.3950***
	(0.0271)	(0.1177)	(0.0299)	(0.1303)
Year FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Observations	182	182	182	182
cities	14	14	14	14
R^2	0.3715	0.5474	0.5996	0.7077

Note: ***, ** and * represent significance levels of 1%, 5%, and 10%, respectively. Clustering robustness standard errors are shown in parentheses.

the control group. Table 6 displays the regression findings. The coefficients of the FTZ establishment are broadly compatible with the estimates presented in the previous empirical section regarding the sign and significant level. The contribution of FTZ creation to regional green technology innovation remains.

4.4. Mechanism investigation

4.4.1. Create the mediating effect model

We employ mediation effect models to assess whether these mechanisms exist:

$$Y_{it} = \alpha_0 + \alpha_1 Treat_i {*} Time_t + \gamma X_{it} + f_i + f_t + \varepsilon_{it} \tag{7}$$

$$M_{it} = \beta_0 + \beta_1 Treat_i {*} Time_t + \beta_2 X_{it} + \theta_i + \theta_t + \varepsilon_{it} \tag{8}$$

$$Y_{it} = \rho_0 + \rho_1 Treat_i {*} Time_t + \varphi M_{it} + \rho_3 X_{it} + \tau_i + \tau_j + \varepsilon_{it} \tag{9}$$

Our primary equation for modeling green technology innovation is equation (7), which integrates the treatment and time variables, along with a set of controls and fixed effects to account for unobserved heterogeneity. To encapsulate the mediating factors, which

Table 6
Results of replacing the treatment group and the control group.

Variables	(1)	(2)	(3)	(4)
	Gie	*Gie*	*Gtfp*	*Gtfp*
Pol	0.0605***	0.0558***	0.0998***	0.0895***
	(0.0068)	(0.0065)	(0.0095)	(0.0086)
Pgdp		0.1468***		0.2258***
		(0.0106)		(0.0140)
Fdi		−0.0377		−0.0856
		(0.0540)		(0.0712)
Hc		−0.1178		−0.2928
		(0.3394)		(0.4475)
Inf		−0.0074		0.0056
		(0.0101)		(0.0133)
Tran		−0.0736***		−0.0973***
		(0.0111)		(0.0146)
Gov		−0.1920***		−0.5650***
		(0.0366)		(0.0483)
Cons	0.5222***	0.5335***	1.0000***	1.0303***
	(0.0043)	(0.0156)	(0.0060)	(0.0205)
Year FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Observations	2977	2977	2977	2977
cities	229	229	229	229
R^2	0.5309	0.5841	0.6829	0.7451

Note: ***, ** and * represent significance levels of 1%, 5%, and 10%, respectively. Clustering robustness standard errors are shown in parentheses.

include the industrial agglomeration level (Hhi) , digital economy development level (Dig) , and governmental support (Gf) , we refer to equation (8). This equation allows us to isolate the direct influence of these mediators on the treatment effect. Finally, the overall model that synthesizes the direct and indirect effects of the treatment on green technology innovation, accounting for both the mediating factors and the full set of controls, is presented in equation (9). The procedure follows: First, determine coefficient α_1's significance in equation (7); if coefficient α_1 is significant, assess β_1 and φ from equations (8) and (9), respectively. There is a mediating impact if both are substantial at the same time.

4.4.2. *Mediating variables*

4.4.2.1. Industrial agglomeration. Many literature have contributed to the measurement of specialized and diverse agglomerations, with the Hirschman-Herfindahl Index (HHI) and the number of employees being the most widely used [19]. On this basis, we use the HHI index to measure the degree of regional industrial agglomeration, which is measured as equation (10):

$$\mathrm{Indagg}_{it} = \sum_{j}^{m}\left(\frac{X_{ij}}{\sum_{i}^{n} X_{ij}}\right)^2 = \sum_{j}^{m} S_{ij}{}^2 \tag{10}$$

Where X_{ij} represents the number of persons engaged in the j industry in region i, and S_{ij} denotes the proportion of individuals working in the j industry in region i to the total number of people employed in the j industry in the country. We deploy the three-industry classification approach ($m = 3$) to evaluate the industrial agglomeration degree. The measurement result needs to be more due to using urban-level data. To facilitate monitoring the impact of industrial agglomeration on the green technology innovation, we amplify the HHI index by 10000 times and record it as Indagg.

4.4.2.2. Digital economy development. Considering the coincidence of indicators and the collinearity of data, this article draws on the methodologies of Zhao T et al. (2020) to select the following metrics for the comprehensive development index of the digital economy: Internet penetration rate (number of Internet broadband users per 100 people), internet-related employees (proportion of computer services and software employees), internet-related output (total telecommunications business per capita), mobile phone penetration rate (number of mobile phone users per 100 people), and digital finance inclusive development index (China Digital Inclusive Finance Index) [20]. The data from the five indicators above are standardized and dimensionally reduced using principal component analysis, and the result is the digital economy's complete development index score, which is reported as Dig.

4.4.2.3. Government support. The proportion of science and technology expenditure in government financial expenditure is used to assess the status of regional government financial science and technology expenditure, denoted as Gf.

4.4.3. *Mechanism results*

Table 7 shows the mediate effect test. When the level of industrial agglomeration (Indagg) serves as the intermediary variable, the regression coefficient β_1 is substantially positive. In column (5) of Table 7, the estimated coefficient ρ_1 of the FTZs is 0.0403. It is significant at the 1% level, suggesting that establishing the FTZs plays a vital mediator role in promoting regional green technology innovation. Externalities of industrial agglomeration, in particular, have a substantial impact on the behavior and performance of firms, which may considerably boost their productivity [21] and modify regional innovation behavior. Columns (3) and (6) of Table 7 reveal the digital economy's mediating effect test findings. Column (6) indicating that the introduction of digital economy has played a crucial mediator role in raising regional green technological innovation. Column (6) suggests that the government's financial investment in research and technology has served as a noteworthy mediator, strengthening the influence of FTZs on green technology innovation. In conclusion, the creation of FTZs can improve the region's performance in green technology innovation through industrial agglomeration, the digital economy, and government support. The results presented in columns (2) and (5) confirm Hypothesis H1: The FTZs can enhance green technology innovation efficiency through industrial agglomeration. Similarly, the findings in columns (3) and (6) validate Hypothesis H2: The FTZs can increase green technology innovation efficiency through the digital economy. Lastly, the outcomes in columns (4) and (7) corroborate Hypothesis H3: The FTZs can boost green technology innovation efficiency through government financial support.

4.5. *Heterogeneity analysis*

4.5.1. *Heterogeneity of inland cities and coastal cities*

As a policy pilot, the FTZ policy is progressively expanding from coastal to interior areas. The consequences of its execution vary due to geographical conditions and economic base differences. The first procedure is to divide the FTZ's provinces into coastal and inland provinces on a provincial level; next, the FTZs are separated into coastal and inland cities using cities as a unit. Table 8 displays the regression findings.

As shown in Table 8, the effect of the FTZ establishment on green technology innovation advancement in both inland provinces and inland cities is stronger than the influence on coastal areas. The reasons for this are, first, the various innovation bases. The coastal FTZs are located in a region with a more outstanding capital stock, infrastructure, and innovation factors than the inland FTZ, which belongs to the innovation highland and has the advantage of port, and has higher green technology innovation efficiency; however, the inland FTZs has a weak innovation base, talent reserve, and relatively backward industrial development, so the implementation of the inland FTZ policy has a more significant incentive effect. Second, the guarantees of the innovation system differ. For inland areas

Table 7
Mechanism test results.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Gtfp	*Hhi*	*Dig*	*Gf*	*Gtfp*	*Gtfp*	*Gtfp*
Pol	0.0412***	0.0220***	0.0076***	0.0008*	0.0403***	0.0249***	0.0394***
	(0.0059)	(0.0049)	(0.0024)	(0.0005)	(0.0059)	(0.0058)	(0.0058)
Hhi					0.0419**		
					(0.0206)		
Dig						0.4326***	
						(0.0487)	
Gf							2.1851***
							(0.2136)
Pgdp	0.2318***	0.0106	−0.0324***	0.0041***	0.2314***	0.3214***	0.2228***
	(0.0134)	(0.0111)	(0.0067)	(0.0011)	(0.0134)	(0.0163)	(0.0132)
Fdi	−0.0967	0.2505***	0.0013	0.0655***	−0.1072	−0.1819**	−0.2397***
	(0.0747)	(0.0619)	(0.0320)	(0.0059)	(0.0748)	(0.0774)	(0.0749)
Hc	0.2975	0.0142	−0.0337	−0.0544*	0.2969	−0.0556	0.4164
	(0.4082)	(0.3383)	(0.2011)	(0.0321)	(0.4081)	(0.4864)	(0.4024)
Inf	0.0151	−0.0531***	−0.0145***	−0.0044***	0.0173	0.0239*	0.0246**
	(0.0119)	(0.0098)	(0.0054)	(0.0009)	(0.0119)	(0.0131)	(0.0117)
Tran	−0.0821***	−0.0361***	−0.0285***	0.0014	−0.0806***	−0.0865***	−0.0852***
	(0.0149)	(0.0124)	(0.0068)	(0.0012)	(0.0150)	(0.0166)	(0.0147)
Gov	−0.4817***	−0.1030***	−0.1049***	−0.0238***	−0.4774***	−0.2966***	−0.4298***
	(0.0441)	(0.0366)	(0.0247)	(0.0035)	(0.0441)	(0.0601)	(0.0438)
Cons	0.9976***	0.2513***	0.6703***	0.0143***	0.9870***	0.2808***	0.9664***
	(0.0192)	(0.0159)	(0.0107)	(0.0015)	(0.0198)	(0.0417)	(0.0191)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3744	3744	2765	3744	3744	2765	3744
cities	288	288	284	288	288	288	288
R^2	0.7177	0.1279	0.2612	0.1499	0.7182	0.3774	0.7267

Note: column (1) reflects the regression results of model (6), while columns (2), (3), and (4) are the estimated results of model (7); columns (5), (6), and (7) are the estimated results of model (8).

Table 8
Regression results of inland and coastal areas.

Variables	Coastal provinces	Inland provinces	Coastal cities	Inland cities
	(1)	(2)	(3)	(4)
	Gtfp	*Gtfp*	*Gtfp*	*Gtfp*
Pol	0.0175*	0.0352***	0.0196	0.0404***
	(0.0103)	(0.0077)	(0.0156)	(0.0067)
Pgdp	0.2187***	0.2320***	0.1703***	0.2360***
	(0.0231)	(0.0158)	(0.0381)	(0.0142)
Fdi	−0.1485	0.3604***	−0.0415	−0.0500
	(0.1245)	(0.0933)	(0.1501)	(0.0876)
Hc	−2.4127***	2.2109***	−3.8925***	1.1443***
	(0.6571)	(0.4927)	(1.1224)	(0.4343)
Inf	0.0237	0.0353**	0.0672***	0.0054
	(0.0189)	(0.0146)	(0.0254)	(0.0135)
Tran	−0.1166***	−0.0085	−0.1590***	−0.0407**
	(0.0240)	(0.0188)	(0.0324)	(0.0171)
Gov	−1.2180***	−0.2999***	−1.0441***	−0.4159***
	(0.1116)	(0.0461)	(0.2230)	(0.0448)
Cons	1.0781***	0.9138***	1.1030***	0.9694***
	(0.0375)	(0.0217)	(0.0644)	(0.0204)
Year FE	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Observations	1469	2275	676	3068
cities	113	175	52	236
R^2	0.6757	0.7802	0.6563	0.7444

Note: ***, ** and * represent significance levels of 1%, 5%, and 10%, respectively. Clustering robustness standard errors are shown in parentheses.

where the institutional framework is weak, the creation of inland FTZs may more quickly and thoroughly exert the innovation impact and boost the green innovation ability. As a result, promoting inland FTZs construction can more completely unleash the potential of green technology innovation in inland locations than in coastal cities.

4.5.2. Heterogeneity between different city sizes

We split the sample data according to the "Notice on Adjusting the Criteria for City Size Classification (2014)". Cities having a population larger than one million are classed as major cities, cities with a population between 0.5 million and one million are classified as medium cities, and cities with a population less than 0.5 million are classified as small cities, with the results presented in

Table 9
Results of different city sizes.

Variables	Large cities	Medium-sized cities	Small cities
	(1)	(2)	(3)
	Gtfp	*Gtfp*	*Gtfp*
Pol	0.0413***	0.0347***	0.0303***
	(0.0110)	(0.0087)	(0.0098)
Pgdp	0.2240***	0.3315***	0.2497***
	(0.0288)	(0.0214)	(0.0201)
Fdi	−0.0941	0.1083	−0.0508
	(0.1233)	(0.1025)	(0.1394)
Hc	0.1164	−1.2958*	−0.3408
	(0.5422)	(0.7467)	(0.8161)
Inf	0.0056	0.0295	0.0375*
	(0.0208)	(0.0182)	(0.0195)
Tran	−0.1101***	−0.0925***	−0.0111
	(0.0264)	(0.0205)	(0.0260)
Gov	−1.4752***	−0.4386***	−0.1704***
	(0.1519)	(0.0782)	(0.0563)
Cons	1.0319***	0.9597***	0.9458***
	(0.0500)	(0.0297)	(0.0261)
Year FE	Yes	Yes	Yes
City FE	Yes	Yes	Yes
Observations	975	1222	1547
cities	75	94	119
R^2	0.6476	0.8110	0.7595

Note: ***, ** and * represent significance levels of 1%, 5%, and 10%, respectively. Clustering robustness standard errors are shown in parentheses.

Table 9. On the one hand, large cities have relatively better economic development and a wealth of technological innovation experience, so the driving effect of FTZ policy on green technological innovation performance is greater than that of medium and small cities; Large cities, on the other hand, face more significant environmental burdens, traffic congestion, and industrial pollution, providing more incentives for large cities to pursue green technology innovation. They are more capable of seizing the core of investment and trade facilitation, further strengthening the city's innovation advantage and agglomeration effect, and attracting many innovative talents and capital. As a result, forming FTZs promotes green technology innovation in large cities more than in small and medium-sized cities.

4.5.3. Heterogeneity among urban geographic locations

We divide the sample data into three groups based on city location: eastern, central, and western regions. Table 10 shows the results from best to worst in policy effect: central, western, and eastern regions. Coupled with the support of major national strategies such as ecological protection and high-quality development of the Yellow River Basin, development of the West, and rural revitalization, the central and western regions are better able to seize the opportunity further to enhance the FTZ's green technological innovation effect and proactively serve and integrate into the high-quality development.

5. Conclusions

In the context of China's vigorous promotion of Free Trade Zones (FTZs) development and the implementation of a green innovation growth strategy, our study focuses on the impact and mechanisms of FTZs on green technology innovation performance, yielding the following main conclusions.

(1) Prominent influence of FTZs on enhancing green technology innovation efficiency: Employing a Difference in Differences approach, alongside panel data from 288 Chinese prefecture-level cities and above from 2008 to 2020, we rigorously analyzed the Yangtze River Economic Belt's development strategy and its effect on green technology innovation efficiency. Our empirical investigation establishes that the inception of FTZs substantially bolsters this efficiency. Rigorous robustness checks, encompassing the substitution of dependent variables, modification of estimation methodologies, and adjustments in control and treatment groups, solidify the reliability of our baseline regression findings. This evidences the authentic and potent impact of the Yangtze River Economic Belt's strategy in augmenting green technology innovation efficiency.

(2) Strategic pathways leveraged by FTZs to augment green technology innovation efficiency: In our analysis, a mediation effect model was deployed to probe the mechanisms through which FTZs influence green technology innovation efficiency. The outcomes of this analysis highlight the pronounced mediation effects resulting from industrial agglomeration, digital economy advancements, and government financial backing.

(3) Geographical and typological disparities in the FTZs' impact and mechanism on green technology innovation efficiency: An in-depth heterogeneity assessment reveals significant variations contingent on city classification and geographical positioning. In terms of city types, FTZs exhibit a more substantial promotional impact on green technology innovation efficiency in inland cities compared to coastal cities, with a notably higher efficacy in larger urban centers versus smaller ones. In terms of geographic location, the influence of FTZs on enhancing green technology innovation efficiency is more marked in the central and western regions than in the eastern parts of China. These insights not only underscore the pivotal role of FTZs in fostering green technology innovation but also contribute significantly to both academic discourse and policy formulation, highlighting the nuanced interplay between economic strategies and sustainable technological advancement across varied regional landscapes. Additionally, these strategic recommendations, derived from our comprehensive study, are aimed at maximizing the potential of FTZs in fostering green technology innovation:

First and foremost, there is a pressing need to amplify efforts in constructing and expanding Free Trade Experimental Zones (FTZs). This entails not only increasing the number and scale of these zones but also enhancing their operational efficacy and innovation capacity. By doing so, we can create more dynamic hubs of economic and technological activity that drive the advancement of green technology innovation.

Secondly, promoting the deepening of industrial agglomeration is crucial. This involves nurturing specialized industrial clusters within the FTZs that can leverage synergies, enhance collaborative innovation, and accelerate the exchange of knowledge and technology. Such concentrated hubs of industry are essential for fostering a vibrant ecosystem conducive to green technology development.

The third recommendation is to expedite the development of the digital economy. This step is fundamental in creating an infrastructure that supports innovation and efficiency. By embracing digital transformation, FTZs can optimize their operational processes, enhance data-driven decision-making, and foster a culture of continuous innovation in green technologies.

Lastly, it is imperative to moderately increase government financial support. This involves not only providing direct financial incentives for green technology projects but also creating a favorable policy environment that encourages private investment and international collaboration. Government backing in terms of financial resources, policy formulation, and infrastructural support will play a pivotal role in catalyzing the growth of green technologies within FTZs.

6. Limitations

Firstly, we recognize the limited scope of indicators employed to assess green technology innovation efficiency. Our primary focus

Table 10
Results of cities in different geographical locations.

Variables	Eastern regions	Central regions	Western regions
	(1)	(2)	(3)
	Gtfp	*Gtfp*	*Gtfp*
Pol	0.0035	0.0578***	0.0411***
	(0.0115)	(0.0084)	(0.0101)
Pgdp	0.2685***	0.1919***	0.2625***
	(0.0221)	(0.0215)	(0.0250)
Fdi	−0.1327	0.2317**	−0.2766
	(0.1093)	(0.0990)	(0.2100)
Hc	−2.2010**	2.8257***	1.6940***
	(0.9007)	(0.5610)	(0.6186)
Inf	0.0799***	−0.0506**	0.0090
	(0.0241)	(0.0242)	(0.0168)
Tran	−0.1417***	0.0269	−0.0871***
	(0.0267)	(0.0190)	(0.0280)
Gov	−0.9474***	−0.3792***	−0.3090***
	(0.0867)	(0.1108)	(0.0618)
Cons	0.9807***	0.9070***	0.9932***
	(0.0397)	(0.0318)	(0.0284)
Year FE	Yes	Yes	Yes
City FE	Yes	Yes	Yes
Observations	1261	1040	1443
cities	97	80	111
R^2	0.7174	0.8621	0.7070

Note: ***, ** and * represent significance levels of 1%, 5%, and 10%, respectively. Clustering robustness standard errors are shown in parentheses.

was on economic and R&D outputs, represented by regional GDP and patent applications. However, a broader spectrum of indicators, encompassing new product sales revenue, the number of new product development projects, and technology market turnover, is vital for a more holistic evaluation. Furthermore, our analysis of non-desirable outputs was limited to industrial waste due to data constraints, omitting the environmental impacts from other sectors. Future research endeavors will be directed towards developing a more comprehensive indicator framework for assessing green technology innovation efficiency.

Secondly, our study's macroscopic, city-based analysis of the effects and mechanisms of FTZs on green technology innovation efficiency may lack validation at the micro-level, specifically at the enterprise level. Given that enterprises are central to green innovation and are key targets of policy measures, our future research will integrate a micro-level approach. This approach will involve analyzing data from publicly listed companies, further segmented by industry and type, to provide a nuanced understanding of how FTZ establishment influences green technology innovation efficiency at the enterprise level.

Thirdly, our research may not have fully explored all potential channels through which FTZs construction affects green technology innovation efficiency. While our study examined mechanisms such as industrial agglomeration, the digital economy, and government financial support, subsequent research will probe additional pathways. This includes assessing the role of FTZs in enhancing green technology innovation efficiency through broader trade liberalization, market integration, and improved efficiency in resource utilization.

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Data availability statement

The raw data supporting the conclusions of this article will not be made publicly available. However, the data can be made available upon reasonable request to the corresponding author.

CRediT authorship contribution statement

Chen Lei: Formal analysis, Data curation, Conceptualization. **Wu Lang:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Conceptualization. **Huang Mei:** Formal analysis, Data curation. **He Fang:** Software, Methodology. **Shen Qiangqiang:** Visualization, Validation.

Declaration of competing interest

We declare that there are no conflicts of interest that could be perceived as influencing the research presented in this manuscript.

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