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Can Carbon Emissions Trading Policies Promote Both the Quantity and Quality of Urban Green Technological Innovation? Evidence from China

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Abstract: Under the "dual carbon" goals, China's green development faces the challenge of innovating amid a "lightweight and heavy-duty" dilemma, necessitating the simultaneous improvement in both the quantity and quality of green technological innovation. Based on panel data from 285 cities in mainland China between 2006 and 2020, this paper investigates the policy effect of carbon emission trading pilot programs on urban green technological innovation from the dual perspectives of innovation quantity and quality, using a difference-in-differences (DID) model. This study found that implementing carbon trading policies significantly increased both the quantity and quality of green technological innovation in pilot cities, and these results remain robust after a series of tests. The mechanism analysis indicated that the policy's promoting effect primarily operates through three channels: decarbonizing industrial structure, increasing R&D investment, and enhancing government attention to environmental issues, which together reshape the urban innovation ecosystem. Further analysis revealed that the policy effect is more pronounced in western regions, cities with low enterprise density, and areas designated as "two control zones". This paper enriches the theoretical understanding of market-based environmental regulation and technological innovation and provides new micro-level evidence for deepening carbon market policies.

Keywords: market-based environmental policy; green technological innovation; innovation quantity; innovation quality; China

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1. Introduction

In recent years, promoting a green and low-carbon transformation of the economy and society has become a global consensus. As the world's second-largest economy and the largest carbon emitter, China made the "3060" dual carbon commitment to the international community in September 2020. To achieve this goal, China has been piloting Carbon Emission Trading Pilot Programs (CETPPs) in seven provinces and cities, including Beijing and Shanghai, since 2013 and officially launched a national carbon market in 2021. By the end of 2023, China's carbon market included 2257 key emitting entities, with a cumulative transaction volume of 442 million tons and a transaction value of approximately RMB 24.9 billion. Through setting emission caps, allocating emission allowances, and allowing allowance trading, carbon trading promotes the optimal allocation of social resources through market-based mechanisms, guiding enterprises to actively engage in energy conservation, emission reduction, and low-carbon technological innovation [1]. It has become a key tool for China in controlling greenhouse gas emissions and driving green economic transformation.

However, in the process of vigorously advancing the low-carbon transformation of the economy, China faces a severe dilemma of "heavy weight but light quality" in innovation development. For a long time, influenced by policy guidance and evaluation mechanisms, local governments in China have prioritized the quantity of innovation over the quality of innovation, leading to the waste of innovation resources and hindering the improvement of the country's overall innovation capacity [2]. In fact, focusing solely on innovation quantity may lead to a "patent bubble" [3], which deviates from the essence of innovation. Only by balancing quantity and quality, and supporting green, low-carbon development through high-quality innovation, can we fundamentally resolve the conflict between economic development and ecological environment, achieve synergistic benefits in pollution reduction and carbon reduction [4], and ultimately help realize the dual carbon goals. Currently, China's economic development has shifted from a stage of rapid growth to one focused on high-quality development. Innovation development urgently needs to transition from a quantity-driven model to a quality-driven model. How to promote green technological innovation to achieve both "quantity and quality growth" under the hard constraints of the "dual carbon" goals is a pressing issue that China needs to address in the post-carbon peak era.

The impact of carbon emissions trading policies on green technological innovation has increasingly attracted academic attention. Existing literature mainly explores this issue from the perspectives of firms, industries, and cities, but there is no consensus regarding the innovative effects of carbon trading. At the firm level, there are three main views on the innovative effects of such policies. Scholars who support the "Porter Hypothesis" argue that carbon emission trading policies significantly promote green technological innovation in firms [5–7], especially in state-owned and large-scale firms, which respond more actively to the policy [4,8]. On the other hand, some scholars argue that firms must balance innovation input costs with emission reduction benefits [9], and that policies may crowd out limited innovation resources, thereby exerting a suppression effect [10–12]. Other studies have found that the impact of the policy on firm innovation performance is not significant or is subject to clear threshold effects [13,14]. At the industry level, the policy effects vary depending on industry characteristics: in sectors such as transportation, construction, and chemicals, the policy shows a significant positive effect, while in industries such as steel, it exhibits a crowding-out effect [15]. Some studies also suggest that the policy weakens the green technological innovation capacity of non-polluting industries [10]. At the city level, research is relatively sparse. Studies indicate that the policy generally promotes urban green technological innovation [16,17], but with significant regional heterogeneity. Municipalities and economically developed eastern regions, with better innovation infrastructure and market environments, show stronger innovation effects [18,19].

The existing literature on the innovative effects of carbon emissions trading policies continues to expand in its research perspectives. On the one hand, in terms of innovation measurement, previous studies have primarily focused on the total number of green patent applications [20,21], with a few attempts to assess innovation quality by comparing different types of patents [8]. Some scholars have found that the policy's effect on green patents, utility models, and invention patents decreases in that order [4]. Other studies have used dynamic Qualitative Comparative Analysis (QCA) methods to reveal that the policy's impact on innovation quantity and quality varies across different contexts [22]. On the other hand, the exploration of the mechanisms through which carbon trading influences innovation has deepened. Carbon pricing mechanisms, technology spillovers, and compliance pressure are considered important direct channels of impact [5], while human capital investment, technological support, and industrial structure upgrading serve as key indirect transmission paths [23,24]. Moreover, differences in firms' innovation capabilities and regional economic development levels significantly moderate the innovation incentives of the carbon market [13].

A review of the existing literature reveals several limitations in current research: First, existing studies have overly focused on micro-level innovation responses of firms, neglecting the systemic effects of carbon trading on reshaping the innovation ecosystem at the urban level. Corporate innovation is embedded within the urban innovation system and is profoundly influenced by factors such as the urban institutional environment and resource allocation. There remains insufficient attention to how carbon trading reshapes the green innovation ecosystem of cities. Second, most studies are limited to the perspective of innovation quantity, with few exploring the impact of carbon trading on the quality and increment of innovation. Overemphasis on the number of patents may induce short-sighted responses from local governments and firms, leading to the misallocation of innovation resources and the proliferation of low-quality patents. Third, the existing literature has not adequately explained the mechanisms through which carbon trading influences urban green innovation, particularly in terms of the transmission paths, which remain insufficiently explored and systematized.

In light of these gaps, this paper, based on panel data from 285 prefecture-level cities in China from 2006 to 2020, systematically examines the impact of the carbon emission trading pilot policy on urban green technological innovation from the perspective of both the quantity and quality of innovation. The aim is to provide important theoretical foundations and policy implications for improving carbon market mechanisms and promoting urban green innovation development.

Compared to existing research, the potential marginal contributions of this paper are as follows: (1) In contrast to the existing literature, which focuses on innovation responses at the firm level [4,12], this study examines how carbon trading reshapes urban innovation ecosystems through mechanisms such as demand-pull, the optimization of factor allocation, institutional improvement, and regional innovation network formation from the perspective of the entire urban innovation system, enriching the theoretical understanding of the role of environmental regulation in technological innovation. (2) Building on the predominant focus in existing research on innovation quantity [16], this study constructs an analytical framework that considers both the quantity and quality of innovation, revealing the multi-dimensional effects of carbon trading on green innovation. (3) This study explores the transmission mechanisms of policy effects. Through mechanisms testing based on industrial structure, R&D investment, and government environmental focus, as well as heterogeneous analysis from the perspectives of geographic location, enterprise density, and environmental regulatory strength, this paper systematically elucidates the transmission paths and boundaries of carbon trading's effects on urban innovation, providing empirical evidence for differentiated carbon market development.

2. Theoretical Foundations and Hypotheses

2.1. Carbon Emission Trading Policies and Urban Green Technological Innovation

As an innovative environmental regulation tool, carbon emission trading policies inject new vitality into urban green technological innovation by setting emission caps and introducing market mechanisms. From the perspective of technological innovation theory, cities, as key components of national innovation systems, host diverse innovation entities, such as enterprises, universities, and research institutions [25]. Under carbon constraints, cities play an important role in the process of green technological innovation. The carbon trading policy, centered on the "Cap-and-Trade" mechanism, establishes regional emission caps that are converted into "emission allowances" allocated to key emitting enterprises. During the pilot phase, cities set differentiated emission cap targets based on their economic development levels and industrial characteristics, with most cities adopting free allocation methods. In the early stages, carbon trading prices in the pilot cities exhibited significant volatility but gradually stabilized as the market matured. By transmitting market signals and optimizing resource allocation, the carbon trading policy has created favorable conditions for urban green technological innovation.

Specifically, carbon trading policies comprehensively promote green technology innovation through multiple pathways. First, the market demand driven by carbon trading leads urban innovation activities to focus on green, low-carbon directions. On the one hand, according to Porter's hypothesis, reasonable environmental regulations can force companies to innovate [26], and the carbon trading mechanism pressures energy-intensive firms to increase their investment in energy-saving and emission-reduction technologies [27]. On the other hand, the establishment of carbon market mechanisms has fostered green consumption preferences, where consumers' preference for low-carbon products further enhances the expected economic returns on innovation investment in related fields [28]. Second, policy implementation has optimized the allocation efficiency of urban innovation resources. Under the pressure of the carbon market, both governments and enterprises tend to allocate more innovation subsidies, research talent, and other innovation factors to the low-carbon technology sector [29], ensuring the rational flow of high-quality resources across entities and industries within cities, breaking down institutional barriers that previously hindered collaborative innovation. At the same time, carbon trading also encourages collaboration between enterprises, universities, and research institutions around carbon reduction goals [30], thus accelerating the transfer and transformation of innovation results. Finally, carbon trading compels local governments to further strengthen their support for green technology innovation. To ensure the achievement of carbon control targets, local governments provide effective safeguards for the external environment of technological innovation through improving institutional arrangements, offering diversified green financial policies, and fostering a culture that values green development [31–33]. These combined market and policy effects have laid a solid foundation for urban green technology innovation.

Driven by these combined effects, the impact of carbon emissions trading policies on urban green technological innovation is multi-dimensional, manifested both in the increased quantity of innovation and the improvement in the quality of innovation. In terms of quantity, driven by sustained low-carbon demand and the effect of innovation resource aggregation, carbon emissions trading policies encourage more urban innovation actors to engage in the green technology sector, leading to rapid growth in patent applications [16]. In terms of quality, with the continuous advancement of the policy, green technology innovation has gradually shifted from quantitative growth to qualitative improvement. On the one hand, the carbon trading mechanism guides resource allocation to low-carbon sectors through price signals, while market competition pressure compels urban enterprises to enhance their technological capabilities to obtain more emission allowances and carbon asset revenues [10]. On the other hand, the dynamic mechanism of survival of the fittest will continually optimize the structure of urban innovation actors, driving the gradual elimination of low-quality and highly homogeneous innovations [4], and guiding green technological innovation toward higher quality. Based on this, the following research hypotheses are proposed:

H1a. *Carbon emissions trading policies can significantly increase the quantity of urban green technological innovation.*

H1b. *Carbon emissions trading policies can significantly enhance the quality of urban green technological innovation.*

2.2. Theoretical Mechanism

2.2.1. Industrial Structure Mechanism

Under the carbon emissions trading policy, urban industrial structures are undergoing a systematic transformation from high-carbon to low-carbon industries. First, the carbon pricing mechanism induces a restructuring effect on industrial competitive advantages. High-carbon industries gradually lose their competitiveness due to the higher costs of emission reductions, while low-carbon industries gain more development opportunities through technological advantages and policy support. The relative decline of high-carbon industries and the rise of low-carbon industries drive a low-carbon adjustment in the industrial structure [24]. Second, in the face of increasingly stringent carbon emission constraints, traditional high-energy-consuming industries urgently need to achieve green transformation through technological innovation, creating significant market demand for upstream green technology industries. The two sectors develop synergistically, jointly promoting the upgrading of the industrial system toward a technology-intensive, low-carbon model [34]. Finally, carbon trading creates favorable conditions for cultivating low-carbon industrial clusters in cities. On the one hand, strict entry thresholds and the survival-of-the-fittest mechanism accelerate the elimination of outdated capacities, thus providing development space for low-carbon industries [17]. On the other hand, value-added benefits and policy dividends attract social capital to rapidly concentrate in the low-carbon sector, enhancing the overall low-carbon innovation capability of the city.

The construction of a low-carbon industrial system is key to resolving the dilemma between economic growth and carbon reduction and is also a crucial support for the development of green innovation in cities. On the one hand, the rise of emerging low-carbon industries generates significant demand for green technological innovation, serving as a new engine for innovation-driven development [35]. On the other hand, the acceleration of low-carbon transformation in traditional industries creates conditions for the broader application of mature green technologies. Furthermore, the technological synergy and industrial linkages between high-carbon and low-carbon industries help optimize the allocation of innovation resources on a larger scale, amplifying the socio-economic effects of green innovation [10]. Based on this, we propose the following hypothesis H2:

H2. *The carbon emissions trading policy can promote urban green technological innovation through industrial structure decarbonization.*

2.2.2. R&D Investment Mechanism

The vitality of urban green technology innovation stems from sustained and sufficient R&D investment, and the carbon emission trading policy addresses the bottleneck of investment constraints by reshaping the input decisions of micro-level agents. First, the carbon emission trading mechanism assigns an economic value to carbon emission allowances, transforming corporate energy-saving and emission-reduction technological innovations into a path for obtaining excess returns [7]. Under this incentive mechanism, firms continuously increase their investments in low-carbon R&D, expand their research teams, and improve laboratory facilities, thereby strengthening the foundation for talent development and platform construction for urban green innovation [36]. Second, local governments, guided by the innovation-driven development strategy, compete to introduce supportive policies, such as setting up special funds and implementing tax incentives, to guide social capital toward accelerating the accumulation in the field of green technology innovation [37]. The aggregation of various R&D resources at the urban level, along with deep industry–university–research collaboration, significantly enhances the targeting and systematization of low-carbon technology R&D, making it more aligned with the needs of industrial development. Finally, the survival-of-the-fittest competitive mechanism in the carbon trading market forces firms to focus on core technological breakthroughs, dynamically optimizing the structure of R&D investment [8]. Under cost constraints, companies are compelled to cut low-level, repetitive R&D efforts with marginal emission-reduction benefits, concentrating limited resources on cutting-edge low-carbon technology research, greatly improving the efficiency of R&D spending and enhancing the quality and effectiveness of innovation outputs. Based on this, the following hypothesis is proposed:

H3. *Carbon emission trading policies can promote urban green technology innovation by increasing R&D investment.*

2.2.3. Government Environmental Attention Mechanism

Local governments play a key role as the implementing agents in the enforcement of environmental policies [38]. The implementation of carbon trading mechanisms has created powerful policy constraints and political incentives for local governments, driving the transformation of urban environmental governance models and, in turn, creating a favorable institutional environment for urban green technology innovation. First, the policy system requires local governments to meet dual-control targets on total carbon emissions and emission intensity, compelling them to place low-carbon development at a strategic level [39]. Local governments have increasingly formulated green and low-carbon development plans, promoted the industrialization of low-carbon technologies, and seized opportunities in the new wave of the green industrial revolution. Second, as the national carbon emission trading policy progresses, the coordination of regional emission reduction policies and the binding of interests have become increasingly close, forcing local governments to break down administrative barriers, strengthen cross-regional low-carbon cooperation, and actively build platforms for sharing innovation resources across regions [40]. This significantly expands the breadth and depth of urban low-carbon innovation linkages and accelerates the construction of regional low-carbon innovation networks. Third, the awakening of environmental awareness at the higher levels of government has radiated and driven a green transformation of governance concepts at all levels. Low-carbon development has gradually been embedded as a guiding principle and value pursuit in local government policymaking. During this process, various policy resources, such as environmental regulations, government spending, and subsidy policies, have been tilted toward the green and low-carbon sectors [41], effectively ensuring the development of low-carbon industries and green technological innovations. Based on this, the following hypothesis is proposed:

H4. *Carbon emission trading policies can promote urban green technology innovation by increasing government attention to environmental issues.*

3. Model Variables and Data Description

3.1. Model Construction

Given the staggered implementation of carbon emissions trading pilot programs across cities in China, this paper uses a difference-in-differences (DID) approach with multiple periods to assess the impact of these pilot programs on urban green technological innovation. By holding other factors constant, the multiple-period DID method allows us to examine whether there are significant differences in the "quantity and quality" of green technological innovation between pilot and non-pilot regions before and after the introduction of the carbon trading policy. Based on existing literature [42], the corresponding multiple-period DID model is specified as follows:

$$GTI_{i,t} = \alpha_0 + \beta_1 DID_{i,t} + \beta_2 Control_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (1)$$

Here, i and t represent regions and time periods, respectively. The dependent variable $GTI_{i,t}$ represents urban green technology innovation, measuring both the quantity and quality of green technology innovation in city i during year t. The core explanatory variable $DID_{i,t}$ is a multi-period difference-in-differences estimator, with $DID_{i,t}$ equal to 1 if city i implemented the carbon emission trading pilot policy in year t, and 0 otherwise. The coefficient β_1 measures the net effect of the pilot policy, that is, the change in innovation performance in cities implementing carbon trading policies relative to cities not implementing such policies.

3.2. Variable Definitions

3.2.1. Dependent Variable

The dependent variable is urban green technological innovation (*GTI*). Green technological innovation refers to the adoption of various technologies aimed at energy conservation and environmental protection during the production and research process. The number of patent applications is widely used as an indicator to represent the level of innovation and track new technologies and technology transfer [43,44]. Among these, green patents are not only considered the core measure of green technological innovation, but are also widely adopted in academic research as an indicator of green technological innovation [45]. According to the classification by China's National Intellectual Property Administration, patents are categorized into three types: invention, utility model, and design patents, with decreasing levels of innovativeness [4]. Invention patents must meet the requirements of "novelty, inventiveness, and practicality", demonstrating high technical creativity and novelty, thus representing high-quality innovation [10]. In light of this, following Hu et al. (2020) [4], this paper uses the total number of green patent applications (including invention, utility model, and design patents) as the basic indicator to represent the "quantity" of technological innovation and the number of green invention patent applications as the core indicator to measure the "quality" of green technology innovation. Specifically, by matching the China National Intellectual Property Office (CNIPA) patent database with the WIPO international patent classification for green technologies, we identify regional green patent applications (*Gpatent*) and green invention patent applications (*GIpatent)*. Furthermore, considering that our research sample consists of cities, we use the natural logarithm of the number of green patent applications and the number of green invention patent applications (plus 1) as indicators for evaluating the quantity and quality of urban green technological innovation.

3.2.2. Explanatory Variables

The explanatory variable is a binary variable representing the carbon emissions trading policy (*DID*). China initiated its carbon market development through local pilot programs, with carbon emission trading pilots established in October 2011 across seven provinces and municipalities: Beijing, Tianjin, Shanghai, Chongqing, Guangdong, Hubei, and Shenzhen. The trading operations in these seven pilot carbon markets commenced successively from 2013, with Shenzhen, Shanghai, Beijing, Guangdong, and Tianjin launching their carbon emission trading pilots in 2013, followed by Hubei and Chongqing in 2014. Following the methodological approach of existing literature [39], this paper constructs a policy pilot dummy variable DID, which takes the value of 1 if city i implemented the carbon emission trading pilot policy in year t and subsequent years and 0 otherwise.

3.2.3. Control Variables

To accurately identify the innovation effect of the policy, following the approach used in previous studies [4], the following control variables are included: economic development level (*PGDP*), level of foreign openness (*FDI*), population size (*Size*), fiscal subsidy level (*Gov*), employment (*Job*), and credit scale (*Loan*). Additionally, city dummy variables (*City*) and year dummy variables (*Year*) are also controlled for. The detailed definitions of these variables are provided in Table 1.

Table 1. Definition of variables.

Variable Type	Variable Name	Variable Symbol	Variable Definition
Dependent Variables	Quantity of green technology innovations	*Gpatent*	Ln (number of green patent applications + 1)
	Quality of green technology innovations	*GIpatent*	Ln (number of green invention patent applications + 1)
Independent Variable	Carbon emission trading policy	*DID*	Interaction term between pilot cities and policy initiation time
Mechanism Variables	Industrial structure	*Industry*	Share of secondary industry in GDP
	R&D investment	*RD*	Log of internal R&D expenditure
	Government attention to environmental issues	*GEA*	Frequency of environmental terms in regional annual government work reports
Control Variables	Economic development level	*PGDP*	Ln (per capita GDP of the city)
	Level of foreign openness	*FDI*	Ln (foreign direct investment in the city)
	Population size	*Size*	Ln (average annual population of the city)
	Government subsidy	*Gov*	Ln (total government subsidies in the city)
	Employment	*Job*	Ln (number of employees in the city's manufacturing sector)
	Credit scale	*Loan*	Ln (year-end loan balance of financial institutions in the city)

3.3. Data Sources

This paper utilizes panel data covering 285 Chinese cities from 2006 to 2020 to assess the innovation effects of carbon trading policies, encompassing the transitional period from the initiation of local carbon market pilots in 2013 to the establishment of the national carbon market in 2021. The local carbon market pilots were implemented sequentially between 2013 and 2014: Shenzhen pioneered the trading in June 2013, followed by Shanghai (November 2013), Beijing (November 2013), Guangdong (December 2013), Tianjin (December 2013), Hubei (April 2014), and Chongqing (June 2014). The original data on city-level green patents is derived from the National Intellectual Property Administration (NIPA) patent database and matched and classified according to the World Intellectual Property Organization (WIPO) International Patent Classification (IPC) Green List. Two innovation indicators are constructed: total city green patent applications and green invention patents. The spatial-temporal information on the carbon emission trading policy is obtained by systematically reviewing official documents from the National Development and Reform Commission (NDRC) and the Ministry of Ecology and Environment. The city-level economic and social data primarily come from the annual China Statistical Yearbook and the China Urban Statistical Yearbook. For missing data, cross-validation and supplementation were carried out using local statistical yearbooks, as well as professional databases, such as Wind and CSMAR. Descriptive statistics are presented in Table 2.

Table 2. Descriptive statistics.

Variable	SD	N	P50	Mean	Min	Max
Gpatent	1298	4275	92	512.4	1	8752
GIpatent	843.8	4275	33	268.4	0	7724
DID	0.254	4275	0	0.069	0	1
Industry	0.100	4275	0.388	0.399	0.086	0.839
RD	1.968	4275	11.810	11.660	1.099	17.060
GEA	31.07	4061	89	90.210	0	339
PGDP	0.708	4275	10.480	10.450	8.717	11.980
FDI	1.913	4275	9.835	9.781	4.635	13.910
Size	0.676	4275	5.920	5.867	3.850	7.175
Gov	0.933	4274	14.53	14.51	12.32	17.21
Job	1.210	4275	1.899	1.932	−1.139	4.839
Loan	1.132	4275	15.990	15.970	13.280	18.390

4. Empirical Results

4.1. Parallel Trend Test

The validity of the DID model relies on the parallel trends assumption [46]. This assumption requires that, in the absence of policy intervention, the green technological innovation trends in the treatment and control cities should be similar. To test this assumption, we followed the approach used in previous studies [47], and employed an event-study methodology. Specifically, using the year 2013 as the baseline, when the carbon emissions trading pilot policy was launched, we constructed interaction terms between the year dummies for the pre-policy (*pre*), current (*current*), and post-policy (*post*) periods and the corresponding policy dummies. To avoid perfect multicollinearity, we excluded the interaction term for the period prior to the policy implementation as the reference group. As shown in Figure 1, the estimated coefficients for the periods before policy implementation are statistically insignificant, suggesting that the treatment and control cities indeed had similar green technological innovation trends prior to the policy, thus supporting the parallel trends assumption. In the policy implementation period, the coefficient becomes significantly positive and subsequently increases in a stepwise fashion, indicating a clear divergence between the treatment and control cities in terms of green technological innovation, with a cumulative policy effect. These results not only validate the robustness of the baseline regression but also suggest that the carbon emissions trading policy has a long-term and sustained positive effect on urban green technological innovation.

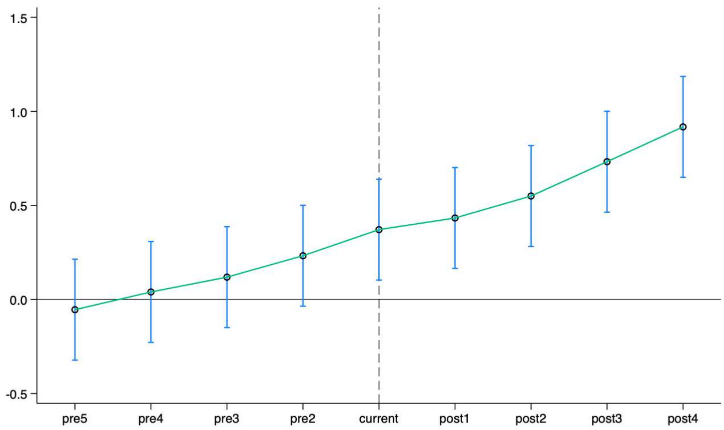

Figure 1. Parallel trends in the data.

4.2. Baseline Regression Results

Table 3 presents the regression results on the impact of the carbon emissions trading policy on the quantity and quality of urban green technological innovation, controlling for both city and year fixed effects. Columns (1) and (3) report the baseline model estimates, while columns (2) and (4) include the control variables. The empirical results reveal that the regression coefficient of the policy variable *DID* on innovation quantity is 0.744, which is statistically significant at the 1% level, indicating a substantial increase in green patent applications in pilot cities compared to non-pilot cities. Similarly, the coefficient on innovation quality (0.888) is statistically significant, demonstrating that the pilot policy substantially enhanced the quality of urban green technology innovation. These findings suggest that carbon trading policies not only facilitate the quantitative expansion of green technology innovation but exhibit an even stronger promotional effect in driving high-quality innovation. These findings are consistent with previous literature on the role of carbon markets in promoting low-carbon technological progress [5,24]. Based on these empirical results, the hypotheses H1a and H1b of this paper are supported by the data.

Table 3. Baseline regression results.

	(1) ***Gpatent***	**(2)** ***Gpatent***	**(3)** ***GIpatent***	**(4)** ***GIpatent***
DID	0.730 ***	0.744 ***	0.822 ***	0.888 ***
	(0.063)	(0.063)	(0.058)	(0.058)
PGDP		−0.205 **		0.048
		(0.084)		(0.077)
FDI		0.053 ***		0.068 ***
		(0.015)		(0.013)
Size		1.781 ***		1.330 ***
		(0.183)		(0.168)
Gov		−0.258 ***		−0.769 ***
		(0.080)		(0.073)
Job		0.130 ***		−0.003
		(0.036)		(0.033)
Loan		−0.171 ***		−0.100 ***
		(0.034)		(0.031)
_cons	0.462 ***	−2.142	0.232 ***	4.014 ***
	(0.011)	(1.458)	(0.011)	(1.339)
City	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
N	4275	4274	4275	4274
adj. R^2	0.7161	0.7284	0.6610	0.6782

Note: The values in parentheses are robust standard errors; *** and ** indicate significance at the 1% and 5% levels, respectively.

4.3. Robustness Checks

4.3.1. PSM-DID

To further validate the causal effect of the carbon emissions trading policy pilot on urban green technological innovation and control for potential sample selection bias, this paper employs the PSM-DID method to exclude potential sources of uncertainty. Propensity score matching (PSM) eliminates initial differences between the treatment and control groups, while the difference-in-differences (DID) method controls for time-invariant omitted variables. This combined approach is widely used in policy evaluation studies [48]. Specifically, this paper applies the radius matching method to construct matched samples. The matching quality check shows that the standardized bias of all covariates is reduced to below 7%, and the *t*-test results are not statistically significant, indicating that the matching effectively reduces systematic differences between the treatment and control groups. The regression results reported in Table 4 indicate that, after controlling for sample selection bias, the carbon emissions trading policy significantly and positively affects the quantity and quality of urban green patents at the 1% significance level, promoting green technological innovation, thus further supporting the findings of this paper.

Table 4. Robustness checks.

	PSM-DID		**One-Period Lag**	
	Gpatent	***GIpatent***	***Gpatent***	***GIpatent***
DID	0.659 ***	0.876 ***	0.729 ***	0.922 ***
	(0.067)	(0.061)	(0.063)	(0.059)
PGDP	−0.168 *	0.102	−0.132	0.108
	(0.089)	(0.082)	(0.086)	(0.079)
FDI	0.044 ***	0.064 ***	0.058 ***	0.072 ***
	(0.016)	(0.014)	(0.015)	(0.014)
Size	1.859 ***	1.310 ***	1.834 ***	1.393 ***
	(0.193)	(0.177)	(0.189)	(0.175)
Gov	−0.196 **	−0.811 ***	−0.222 ***	−0.804 ***
	(0.086)	(0.079)	(0.083)	(0.077)
Job	0.209 ***	0.004	0.096 ***	−0.026
	(0.042)	(0.038)	(0.037)	(0.034)
Loan	−0.190 ***	−0.111 ***	−0.158 ***	−0.095 ***
	(0.036)	(0.033)	(0.034)	(0.032)
_cons	−3.671 **	4.388 ***	−3.854 **	3.541 **
	(1.546)	(1.421)	(1.526)	(1.409)
City	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
N	3992	3992	3989	3989
adj. R2	0.7228	0.6732	0.7554	0.7085

Note: The values in parentheses are robust standard errors; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

4.3.2. Dynamic Effect Test

Given the significant time accumulation characteristic of green technological innovation, this paper examines the long-term impact of the carbon emissions trading policy through a dynamic effect test. Specifically, we construct a one-period lag model for both the quantity and quality of green technological innovation and perform regression analysis. The results show that the policy effect in the lagged one-period model is significantly positive for both innovation indicators at the 1% level, with the coefficient size notably larger than in the contemporaneous model. This suggests that the carbon emissions trading policy has a sustained impact on green technological innovation, with the policy effect progressively strengthening over time.

4.3.3. Excluding Policy Interference

To avoid potential bias in the estimation results due to the influence of other policies on urban green technological innovation, this study excludes observations that may be affected by such policies through sample selection. Specifically, the sample excludes cities affected by China's low-carbon city pilot program implemented in 2010, as well as observations after the implementation of the Environmental Protection Tax Law of the People's Republic of China in 2018. The regression results in Table 5 show that, after excluding these potentially policy-contaminated samples, the positive effects of carbon trading policies on both the quantity and quality of urban green technological innovation slightly decrease but remain statistically significant. This suggests that the core findings of this study are robust and not substantially affected by contemporaneous environmental policies.

Table 5. Excluding the interference of relevant policies.

	Excluding Environmental Protection Laws and Low-Carbon Pilot Programs	
	Gpatent	***GIpatent***
DID	0.550 ***	0.385 ***
	(0.059)	(0.043)
PGDP	−0.179 **	−0.125 **
	(0.079)	(0.058)
FDI	0.069 ***	0.052 ***
	(0.013)	(0.010)
Size	1.503 ***	0.953 ***
	(0.163)	(0.119)
Gov	0.022	−0.011
	(0.079)	(0.057)
Job	0.107 ***	0.046 *
	(0.033)	(0.024)
Loan	−0.130 ***	−0.068 ***
	(0.031)	(0.022)
_cons	−5.544 ***	−3.364 ***
	(1.338)	(0.976)
City	Yes	Yes
Year	Yes	Yes
N	3614	3614
adj. R^2	0.6745	0.5872

Note: The values in parentheses are robust standard errors; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

4.3.4. Placebo Test

Although the baseline regression has controlled for the main factors influencing urban green technological innovation, potential omitted variable bias may still affect the accuracy of the estimates. To address this, a placebo test is conducted, following the methodology used in previous studies [24]. Specifically, treatment variables are randomly generated, and 500 regressions are performed to examine their impact on the quantity and quality of green technological innovation. The kernel density estimates in Figures 2 and 3 show that the distribution of the random coefficients follows a normal distribution centered around zero, with the majority of coefficients being statistically insignificant. This suggests that there is no significant omitted variable bias in the baseline regression results, and the estimates are robust.

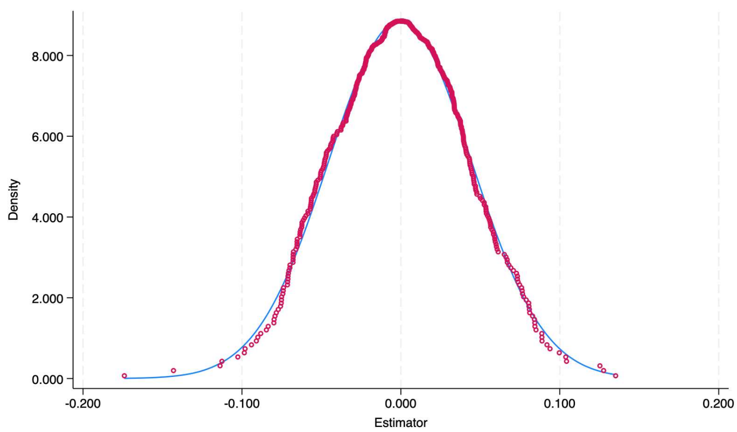

Figure 2. Placebo test for the number of green patent applications.

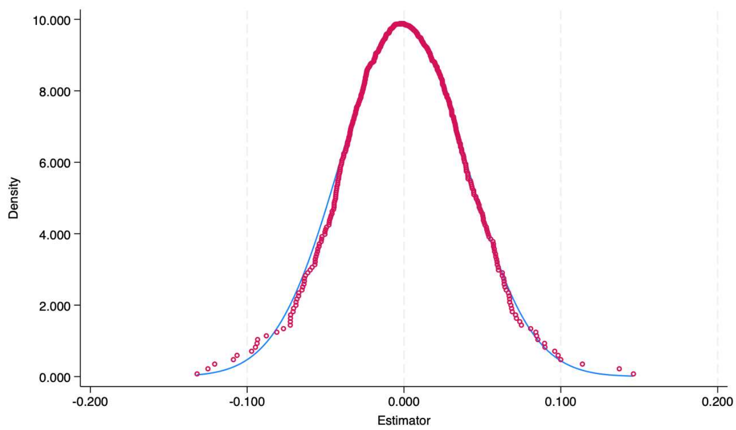

Figure 3. Placebo test for the quality of green patents.

5. Mechanism Analysis

5.1. Industrial Structure Effect

The industrial structure reflects the distribution of the proportions of different industrial sectors within a city. Due to significant differences in production processes, resource consumption, and carbon emission intensities across industries, changes in the industrial structure have an important impact on the level of urban green technological innovation. The secondary sector, which mainly includes manufacturing and construction industries, is the primary source of energy consumption and carbon emissions in cities [10,39]. According to the China Urban Statistical Yearbook, manufacturing and heavy industries account for the majority of energy consumption within the secondary sector, with high-energy-consuming and high-carbon-emission industries being particularly concentrated in this category. Following existing studies [39], this paper uses the proportion of the secondary sector's added value to GDP as an indicator of a city's industrial structure. Generally, a higher proportion of the secondary sector indicates that high-energy-consuming and high-carbon-emission industries dominate the urban economy, which may inhibit green technological innovation at the city level.

The regression results are reported in Table 6. Column (3) shows that carbon emission trading policy has a significant negative impact on the industrial structure variable, with a regression coefficient of -0.018, which is significant at the 1% level. This indicates that the implementation of carbon emission trading policy reduced the proportion of secondary industry in urban economies, promoting the low-carbon transformation of the industrial structure. This occurs because the policy compels high-energy-consuming and high-emission industries to optimize production processes and upgrade technological levels through allowances restrictions and trading mechanisms. This process reduces the economic share of high-carbon industries. Previous studies have shown that a decrease in secondary industry proportion can effectively reduce urban overall carbon emission intensity and alleviate energy consumption and environmental pressure, thereby creating a more conducive environment for green technology innovation [49]. Furthermore, the low-carbon transformation of the industrial structure provides more resource support and market demand for green technology research, development, and application, thus significantly promoting green technology innovation [50]. Overall, carbon emission trading policy lays an important foundation for green technology development by adjusting the industrial structure and reducing the proportion of high-pollution, high-energy-consuming secondary industries. This aligns with the theoretical discussion above, further verifying that industrial structure decarbonization is a crucial transmission mechanism through which carbon emission trading policy influences urban green technology innovation.

Table 6. Mechanism tests.

	(1) *Gpatent*	(2) *GIpatent*	(3) *Industry*	(4) *RD*	(5) *GEA*
DID	0.744 ***	0.888 ***	−0.018 ***	0.159 ***	0.068 **
	(0.063)	(0.058)	(0.003)	(0.052)	(0.034)
PGDP	−0.205 **	0.048	−0.073 ***	−0.231 ***	−0.103 **
	(0.084)	(0.077)	(0.004)	(0.070)	(0.046)
FDI	0.053 ***	0.068 ***	0.001 *	−0.005	0.005
	(0.015)	(0.013)	(0.001)	(0.012)	(0.008)
Size	1.781 ***	1.330 ***	−0.004	−0.297 *	0.351 ***
	(0.183)	(0.168)	(0.009)	(0.152)	(0.099)
Gov	−0.258 ***	−0.769 ***	−0.021 ***	0.103	−0.059
	(0.080)	(0.073)	(0.004)	(0.066)	(0.047)
Job	0.130 ***	−0.003	0.000	0.008	−0.039 **
	(0.036)	(0.033)	(0.002)	(0.030)	(0.020)
Loan	−0.171 ***	−0.100 ***	0.003 **	−0.101 ***	−0.027
	(0.034)	(0.031)	(0.002)	(0.028)	(0.019)
_cons	−2.142	4.014 ***	1.424 ***	9.677 ***	1.672 **
	(1.458)	(1.339)	(0.069)	(1.216)	(0.810)
City	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
N	4274	4274	4274	4274	4060
adj. R^2	0.7284	0.6782	0.8983	0.9134	0.2894

Note: The values in parentheses are robust standard errors; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

5.2. Innovation Input Effect

The level of innovation input in a city plays a crucial role in green technological innovation. Government R&D expenditures, research funding from universities, and enterprise R&D investments are key factors driving technological innovation in cities. Higher R&D investments help foster an innovative atmosphere, attract high-tech talent, and enhance the overall green innovation capacity of a city. In this paper, following the approach of previous studies [13], we measure the level of innovation input using the logarithm of internal R&D expenditure as a proxy for the intensity of urban R&D investment.

The regression results are reported in Table 6. Column (4) shows that the carbon emission trading policy has a significant positive impact on urban innovation input, with a regression coefficient of 0.159, which is significant at the 1% level. This indicates that the carbon emission trading policy has significantly promoted innovation input in cities. Previous studies have shown that R&D investment is a major driver of technological innovation, and direct government R&D funding support can significantly boost green technological innovation in cities [51]. Based on the regression results in columns (1), (2), and (4) of Table 6, as well as existing literature, it can be concluded that the carbon emission trading policy has incentivized cities to increase R&D investments, thereby providing essential human and material resources for green technological innovation, which has significantly enhanced the quantity and quality of urban green patents. Innovation input is, therefore, an important transmission mechanism through which the carbon emission trading policy influences green technological innovation.

5.3. Government Environmental Attention Effect

The degree of local government attention to environmental protection and green development influences the formulation and enforcement of related policies and regulations, which in turn impacts the external environment for green technological innovation in cities. Drawing on previous research [41], this paper measures the environmental attention of local governments through the textual analysis of government work reports. Specifically, we analyze the frequency of keywords such as "environment", "pollution", "ecology", "green", "energy-saving", and "emission reduction" in government work reports over the years, then apply the Term Frequency-Inverse Document Frequency (TF-IDF) algorithm to assign weights and obtain an indicator reflecting the level of government environmental attention. A higher value of this indicator indicates greater local government emphasis on ecological governance and a greater likelihood of implementing policies that encourage green technological innovation.

The regression results are reported in Table 6. Column (5) shows that the carbon emission trading policy has a significant positive impact on government environmental attention, with a regression coefficient of 0.068, significant at the 1% level. This suggests that the carbon emission trading policy pilot has increased local governments' focus on environmental issues. This finding is consistent with the views of existing literature [41]. Previous studies have shown that an increase in local government environmental attention often leads to stricter emission reduction constraints and more active green industry support policies, which undoubtedly provide strong institutional incentives for green technological innovation in cities [36]. Environmental regulations by the government are an important means of encouraging enterprises to engage in green technological innovation and can significantly promote urban green technological innovation [16]. Therefore, based on the regression results in columns (1), (2), and (5) of Table 6, as well as the existing literature, it is reasonable to infer that enhancing government environmental attention is also an important transmission mechanism through which the carbon emission trading policy influences urban green technological innovation.

6. Further Discussion

6.1. Geographic Heterogeneity

Given the significant regional differences in innovation capabilities across China, and based on the regional classification standards in the China Statistical Yearbook, this paper sample is divided into three major economic regions: Eastern, Central, and Western China. This allows for an in-depth examination of the differentiated effects of carbon emission trading policies on green technological innovation across these regions.

The regression results in Table 7 show that in the eastern region, the carbon emissions trading policy has a coefficient of 0.468 for green innovation quantity and 1.186 for green innovation quality, both of which are significant at the 1% level. This indicates that the policy effect in the eastern region is more prominent in improving the quality of green innovation, while its impact on innovation quantity is relatively weaker. The eastern region, characterized by its developed economy, abundant innovation resources, mature carbon market mechanisms, and stringent environmental regulations [5], provides a favorable environment for the policy to promote high-quality green innovation through market mechanisms and resource optimization. However, given the region's already well-established innovation ecosystem, the marginal effect of the policy is primarily concentrated on quality improvement rather than the large-scale expansion of innovation quantity.

In contrast, in the central region, the policy's impact is significantly weaker compared to the eastern region, with coefficients of 0.288 for innovation quantity and 0.141 for innovation quality, both of which are significant at the 1% level, but with relatively small magnitudes. This reflects the central region's limitations in innovation resources, market mechanisms, and policy implementation capacity. The region's long-term reliance on traditional industrial development paths and its transitional position between the eastern and western regions result in weaker resource agglomeration effects of the policy, limiting its incentive effects [23]. As a result, while the policy shows some degree of innovation promotion in the central region, the overall effect remains limited.

Table 7. Geographic heterogeneity test.

	Eastern *Gpatent*	**Eastern** *GIpatent*	**Central** *Gpatent*	**Central** *GIpatent*	**Western** *Gpatent*	**Western** *GIpatent*
DID	0.468 ***	1.186 ***	0.288 ***	0.141 ***	3.199 ***	1.555 ***
	(0.112)	(0.114)	(0.082)	(0.050)	(0.242)	(0.164)
PGDP	−0.662 ***	0.354 *	0.290 **	0.174 **	0.187 *	0.140 **
	(0.199)	(0.203)	(0.114)	(0.070)	(0.097)	(0.066)
FDI	0.203 ***	0.295 ***	0.035 *	0.020	0.028 *	0.016 *
	(0.039)	(0.040)	(0.021)	(0.013)	(0.015)	(0.010)
Size	0.632	0.818 *	1.823 ***	1.064 ***	1.896 ***	1.161 ***
	(0.426)	(0.435)	(0.201)	(0.123)	(0.263)	(0.178)
Gov	−1.142 ***	−2.609 ***	0.405 ***	0.198 **	0.030	0.016
	(0.182)	(0.186)	(0.127)	(0.078)	(0.082)	(0.056)
Job	0.294 ***	−0.114	0.072 *	0.028	0.084 *	0.059 **
	(0.091)	(0.093)	(0.042)	(0.025)	(0.043)	(0.029)
Loan	0.217 ***	0.165 **	−0.298 ***	−0.159 ***	−0.258 ***	−0.149 ***
	(0.064)	(0.066)	(0.055)	(0.033)	(0.051)	(0.034)
_cons	14.605 ***	24.723 ***	−15.036 ***	−8.516 ***	−9.074 ***	−5.942 ***
	(3.332)	(3.400)	(1.981)	(1.212)	(1.839)	(1.248)
City	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
N	1515	1515	1500	1500	1259	1259
adj. R^2	0.7701	0.7266	0.6147	0.5628	0.7033	0.6088

Note: The values in parentheses are robust standard errors; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

In the western region, the policy has the most significant impact on both innovation quantity and quality, with coefficients of 3.199 and 1.555, respectively, both of which are significant at the 1% level. This indicates that the western region has achieved remarkable outcomes in green technological innovation following policy implementation, particularly in patent quantity. The potential explanation is that the high proportion of energy-intensive industries in the western region leads to greater pressure for green transformation under the carbon market policy. Additionally, the region's relatively weak innovation foundation creates ample room for improvement. Moreover, as the western region absorbs industrial transfers from the eastern region, the accompanying technological spillovers provide additional support for its green innovation development [21]. Consequently, compared to the eastern and central regions, the western region exhibits more pronounced policy effects.

In summary, the differences in policy effects across regions primarily reflect variations in economic development levels, innovation resource endowments, and policy transmission mechanisms. The eastern region focuses on high-quality innovation, with the policy effect concentrated on enhancing the technical content and innovation level of green technologies. The central region, with weaker innovation resources, finds it difficult to fully realize the policy's incentive effects, resulting in limited promotion outcomes. In the western region, the low starting point and resource restructuring effects driven by the policy significantly boost both innovation quantity and quality. This comparative analysis further verifies that the policy's impact varies according to regional characteristics, underscoring the importance of designing differentiated policies tailored to regional conditions.

6.2. Heterogeneity of Firm Density

The impact of carbon emission trading policies on urban green technological innovation may exhibit heterogeneity based on firm density. In this paper, cities are divided into high- and low-density groups based on the median number of industrial firms, and the analysis is conducted accordingly. The regression results presented in Table 8 reveal that in regions characterized by low enterprise density, the carbon trading policy exhibits regression coefficients of 0.738 and 1.097 on green technology innovation quantity and quality, respectively, both of which are statistically significant at the 1% level, with a more pronounced effect on quality. This indicates that in regions with lower enterprise density, the policy not only significantly enhanced the total volume of green patent applications but demonstrated an even stronger effect on invention patents, highlighting its potential in fostering high-quality green technology innovation. In contrast, in regions with high enterprise density, the policy's effects on both the quantity and quality of green technology innovation lack statistical significance, suggesting a relatively limited promotional effect in these areas.

Table 8. Heterogeneity test of firm density.

	Low Business Density ***Gpatent***	**High Business Density** ***Gpatent***	**Low Business Density** ***GIpatent***	**High Business Density** ***GIpatent***
DID	0.738 ***	0.007	1.097 ***	−0.013
	(0.098)	(0.016)	(0.095)	(0.009)
PGDP	−0.683 ***	−0.022	−0.051	0.003
	(0.165)	(0.014)	(0.160)	(0.007)
FDI	0.090 **	−0.004 *	0.184 ***	−0.002 **
	(0.037)	(0.002)	(0.036)	(0.001)
Size	1.747 ***	0.249 ***	1.717 ***	0.134 ***
	(0.337)	(0.033)	(0.326)	(0.018)
Gov	−0.305 *	0.020	−1.622 ***	0.013 **
	(0.156)	(0.013)	(0.151)	(0.007)
Job	−0.057	−0.004	−0.228 ***	−0.005
	(0.068)	(0.006)	(0.066)	(0.003)
Loan	−0.579 ***	0.009	−0.357 ***	0.002
	(0.073)	(0.006)	(0.070)	(0.003)
_cons	10.598 ***	−1.444 ***	19.008 ***	−0.918 ***
	(2.937)	(0.247)	(2.844)	(0.130)
City	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
N	2130	2124	2130	2124
adj. R^2	0.7682	0.6549	0.7143	0.6167

Note: The values in parentheses are robust standard errors; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

This discrepancy may be attributed to the following reasons: First, regions with low enterprise density typically have weaker innovation foundations and fewer enterprises, leading to a more concentrated resource allocation under the policy, resulting in more significant marginal improvements after policy implementation [52]. Moreover, low-density regions usually face less market competition pressure, providing enterprises with more resources and space to invest in long-term technological innovation. Meanwhile, the local governments in these regions can implement more precise policy guidance and supervision, thereby improving the execution efficiency of carbon trading policies. Conversely, in regions with high enterprise density, intense market competition may lead enterprises to favor short-term behaviors, weakening the policy's incentive effect on green technology innovation. These findings further support the significant promotional effect of the policy in less developed regions and areas with weak innovation foundations. This is consistent with both our earlier conclusion regarding the significant policy effects in western regions and existing research suggesting that environmental policies can more effectively promote green technology innovation in economically underdeveloped regions [49].

6.3. Heterogeneity of Environmental Regulation Intensity

To explore the moderating effect of environmental regulation intensity on the carbon trading policy's effectiveness, this paper follows the approach of previous research [53] and conducts a subgroup analysis based on whether cities are included in the dual control areas for acid rain and sulfur dioxide (hereinafter referred to as the "Two Control Zones"). Starting in 1998, China designated key cities for inclusion in the Two Control Zones and implemented specialized control measures. The regression results presented in Table 9 demonstrate that in Two Control Zones, the carbon trading policy exhibits regression coefficients of 0.788 and 1.082 on green technology innovation quantity and quality, respectively, both of which are statistically significant at the 1% level. These findings indicate that in regions characterized by stronger environmental regulations, the policy significantly stimulated the growth of total green patent applications, with an even more substantial effect on high-quality green invention patents. In contrast, in areas outside the Two Control Zones, the policy's coefficients on both innovation quantity and quality lack statistical significance, indicating that the carbon trading policy failed to generate significant momentum for green technology innovation in regions with weaker environmental regulations.

Table 9. Heterogeneity test of environmental regulation intensity.

	Two Control Zones	**Areas Outside the Two Control Zones**	**Two Control Zones**	**Areas Outside the Two Control Zones**
	Gpatent	***Gpatent***	***GIpatent***	***GIpatent***
DID	0.788 ***	−0.034	1.082 ***	−0.030
	(0.094)	(0.054)	(0.090)	(0.035)
PGDP	−0.473 ***	0.097 *	0.127	0.056 *
	(0.159)	(0.050)	(0.151)	(0.032)
FDI	0.151 ***	0.019 **	0.168 ***	0.010 *
	(0.029)	(0.008)	(0.027)	(0.005)
Size	1.083 ***	1.422 ***	1.152 ***	0.774 ***
	(0.292)	(0.138)	(0.277)	(0.088)
Gov	−0.196	−0.047	−1.620 ***	−0.017
	(0.159)	(0.046)	(0.151)	(0.029)
Job	0.207 ***	0.034	−0.039	0.019
	(0.064)	(0.022)	(0.061)	(0.014)
Loan	−0.351 ***	0.008	−0.135 **	−0.001
	(0.062)	(0.021)	(0.059)	(0.013)
_cons	5.830 **	−8.677 ***	16.483 ***	−4.818 ***
	(2.594)	(0.959)	(2.466)	(0.611)
City	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
N	2219	2055	2219	2055
adj. R^2	0.7504	0.5803	0.7030	0.5141

Note: The values in parentheses are robust standard errors; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

This heterogeneous effect can be attributed to two primary factors: First, cities within Two Control Zones face heightened pressure for energy conservation and emission reduction, enabling local governments to strengthen enterprise pollution control requirements and support green innovation activities through mechanisms such as subsidies [54], thereby enhancing urban green technology innovation. Second, these cities possess a more robust environmental regulation foundation, facilitating synergistic effects between carbon trading and other environmental policies, which further stimulates green innovation investment. These synergistic effects yield the enhanced innovation-promoting outcomes of carbon trading policy in regions with stronger regulatory frameworks. This finding corroborates Zhai et al. (2023)'s conclusion [18] that carbon trading policy demonstrates greater efficacy in promoting urban green development efficiency in regions with superior environmental governance.

7. Conclusions and Policy Implications

This paper uses a quasi-natural experiment based on the design of China's carbon emission trading pilot policy, employing panel data from 285 cities in China between 2006 and 2020 as the sample. A difference-in-differences (DID) model was constructed to examine the relationship, mechanisms, and heterogeneity between carbon emission trading and urban green technological innovation. The results show the following: First, carbon emission trading significantly enhances both the quantity and quality of urban green technology innovation, with a more substantial promotional effect on innovation quality. This conclusion remains robust after conducting parallel trend tests, PSM-DID, placebo tests, dynamic effect tests, and controlling for the interference of contemporaneous policies. Second, mechanism tests reveal that carbon emission trading positively influences urban green technological innovation by decarbonizing industrial structure, increasing innovation investment, and enhancing governmental attention to environmental issues. Third, the influence of carbon emission trading policy on urban green technology innovation exhibits substantial heterogeneity across different regional characteristics and urban conditions. Geographically, the policy demonstrates its strongest effects in western regions, with the promotional impact on green technology innovation quantity surpassing that observed in eastern and central regions. With respect to enterprise density, the policy's stimulative effects are significantly more pronounced in cities characterized by low enterprise density compared to their high-density counterparts, with a particularly notable enhancement in innovation quality in low-density cities. Moreover, regarding environmental regulation intensity, cities within "Two Control Zones" demonstrate more substantial policy effects, particularly in fostering high-quality green technology innovation, while cities outside these zones exhibit statistically insignificant policy effects.

Based on these findings, this paper offers the following policy recommendations: First, optimize the national carbon market's operational mechanism to enhance market vitality and efficiency. While the establishment of the national carbon market has laid an institutional foundation for promoting green and low-carbon development, there remains considerable room for improvement in its coverage and operational efficiency. It is recommended that the government gradually expand the sectoral coverage of the national carbon market, incorporating more high-emission industries into the trading system. Meanwhile, the carbon allowance allocation mechanism should be improved by gradually increasing the proportion of paid allocation to guide enterprises toward technological innovation for carbon reduction. Second, improve supporting policies to promote industrial structure decarbonization and expand innovation investment. To fully unleash the green innovation potential of the carbon market, the government should implement measures complementary to carbon trading policies. These include accelerating the establishment of a comprehensive green financial system to provide funding support for green technology R&D; promoting the dissemination and application of low-carbon technologies to accelerate the market transformation of green technologies; and encouraging enterprises to increase R&D investment, particularly in high-quality innovation. Third, develop differentiated carbon market policies tailored to local conditions. Policy implementation should fully consider the heterogeneity of regional characteristics and urban conditions. For instance, western regions should receive enhanced policy support, with greater financial and technical assistance to help achieve industrial upgrading and low-carbon development through green technology innovation. For cities with lower industrial enterprise density, policy incentives should be strengthened to compensate for innovation disadvantages stemming from weak enterprise foundations. For "Two Control Zone" cities with stricter environmental regulations, carbon market reforms can be further deepened by strengthening carbon pricing mechanisms to enhance the incentive effects for high-quality green technology innovation.

Although this paper expands upon existing research, there are several limitations. First, due to data availability constraints, this study uses patent data as the sole measure of urban green technological innovation. Future research could explore richer data sources and employ a more comprehensive indicator system. Second, while this study examines the heterogeneity of the policy effects under different regional, enterprise density, and environmental regulation conditions, there is still room for further investigation into the policy's heterogeneous impacts across additional dimensions to better understand the mechanisms and boundary conditions of the policy.

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