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The Impact of Carbon-Emission Trading Scheme Policies on Air Quality in Chinese Cities

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Abstract: Air quality issues have a significant impact on human health and are an important issue affecting sustainable development. With the implementation of China's carbon-emission trading scheme, carbon emissions have been effectively reduced, which has a potential impact on air quality. This article uses a time-point difference-in-differences model to analyze the impact of the implementation of a carbon-emission trading scheme on the air quality in 284 cities in China from 2008 to 2021. During the inspection, the impact of policies on overall air quality and on various types of air pollutants was discussed separately. The research results show that the implementation of the carbon-emission trading scheme helps improve urban air quality issues, reduce the concentration of air pollutants such as $PM_{2.5}$ and SO_2, and improve the urban environment; with controlled variables, it has reduced $PM_{2.5}$ by 2.548 units, SO_2 by 0.180 units, NO_x by 0.295 units, and has promoted the sustainable development of cities. In addition, the policy mainly has a positive impact on air quality by promoting green technology innovation and industrial upgrading, further demonstrating the spillover effect of the policy. There is also some regional heterogeneity in the policies, especially in the central and western regions, where the reduction effect of SO_2 and nitrogen oxides is not significant.

Keywords: carbon-emission trading scheme; air quality; sustainable development; green technology innovation

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1. Introduction

Air quality plays a significant role in the issue of sustainable development. It is not only directly related to people's health and quality of life but also closely tied to the sustainable development of cities [1]. The deterioration of air quality leads to atmospheric pollution, impacting the urban ecological environment. Prolonged atmospheric pollution can result in vegetation damage, water source contamination, soil degradation, and other issues, severely disrupting the city's ecological balance [2]. At the same time, air pollution directly affects people's respiratory and cardiovascular health, reduces residents' quality of life, and may trigger mental health problems such as anxiety and depression. Additionally, factors such as the level of urban development, industrial structure, energy mix, and traffic conditions also exert substantial influence on air quality [3]. Therefore, air quality serves as one of the crucial indicators for urban sustainable development.

China's air quality has undergone remarkable changes over the past few decades. With the rapid industrialization and urbanization, air quality issues were once severe, but the Chinese government demonstrated a steadfast commitment to addressing them. Social protection has become an essential tool for reducing vulnerability and enhancing resilience [4]. Since the implementation of the "Air Pollution Prevention and Control Action Plan" in 2013, China has achieved significant overall improvements in air quality through a series of emission control measures and policies. The data show that from 2013 to 2022, the annual average concentration of $PM_{2.5}$ across China decreased by approximately 56%,

and the annual average concentration of SO_2 dropped by about 78%. China has become the country with the fastest-improving air quality in the world. To continue enhancing air quality, the Chinese government has continuously introduced new policies, such as the "Action Plan for the Continuous Improvement of Air Quality", aiming to reduce the $PM_{2.5}$ concentration in cities at and above the prefecture level by 10% compared to 2020 levels and control the ratio of days with heavy and above pollution within 1% by 2025. These initiatives fully demonstrate the Chinese government's determination to tackle air quality issues and its steadfast belief in promoting high-quality economic development in harmony with environmental protection.

The Chinese National Development and Reform Commission released the "Notice on Carrying out Pilot Work on Carbon Emission Trading" in 2011, enabling seven provincial administrative regions—Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong, and Shenzhen—to start pilot projects on carbon-emission trading. Since then, the carbon-emission trading scheme (CETS) has had an impact on China's sustainable development.

Shenzhen launched the carbon emission trading scheme program in the urban stage on 18 June 2013. Shenzhen became the first pilot market to start trading, and one of the first national pilots as a result. Beijing, Tianjin, Shanghai, and Guangdong launched carbon-emission market pilots at the end of the same year. In April and June of 2014, respectively, Hubei and Chongqing launched their pilot programs for pricing carbon emissions. Pilot trading was implemented in September 2016 by Fujian, making it the first carbon market established in a non-pilot region. On 16 July 2021, a single nationwide market was formally formed as the national carbon-emission trading market. Its trading center is Shanghai, while the carbon quota registration system is located in Wuhan. With the launch of the national carbon-emission trading market, China's carbon market—which now covers the greatest amount of greenhouse gas emissions worldwide—entered the national functioning stage.

CETS has significantly contributed to curbing carbon dioxide emissions in pilot areas [5]. CETS has been piloted since 2011, and from the local to the national unified market establishment in China, it has gone through more than 10 years of mature experiments. This raises a question: when CETS influences corporate behavior, will there be a technology spillover due to technological innovation and other mechanisms, thereby improving air quality?

On the one hand, the implementation of the CETS has driven the optimization and upgrading of the industrial structure. Industries with high energy consumption and high emissions face greater cost pressures in the carbon-emission trading market, thereby prompting these industries to undertake technological innovations and revolutionary upgrades to reduce carbon emissions. The optimization of the industrial structure helps to reduce the emission of air pollutants at the source, thereby improving air quality [6]. On the other hand, the implementation of CETS may be influenced by regional economic dependencies and conflicts of interest. Some regions may be highly dependent on industries with high energy consumption and high emissions, which face greater cost pressures in the carbon-emission trading market. Due to regional influences that create heterogeneity among areas, the implementation effectiveness of CETS may be affected [7].

Utilizing a time-varying DID approach, this study evaluates the efficacy of CETS on urban air quality across 284 Chinese cities from 2008 to 2021. The regression outcomes demonstrate that the CETS pilot significantly ameliorates key urban air quality indicators. To bolster the credibility of these findings, the study incorporates parallel trend and placebo tests. The research further delves into the mechanisms driving air quality enhancements through CETS, highlighting the pivotal roles of green technological advancements and the modernization of industrial structures.

The study's original contributions are multifaceted: First, although existing literature has discussed the impact of carbon-emission trading policies on $PM_{2.5}$, there has been little discussion on the overall impact on air quality. In addition, in terms of analytical methods, most of the literature also uses fixed-effect models to discuss the impact of carbon-emission trading volume on air quality, which has potential endogenous problems. Therefore, this

article uses a difference-in-differences model to discuss the impact of carbon-emission trading policies on overall air quality, which can both expand the scope of discussion and reduce the impact of endogenous issues. Secondly, this article analyzes the impact of green technology innovation and industrial upgrading on air quality, which can help to show policy adjustments and better leverage the spillover effects of policies.

The paper's following sections are arranged as follows: a review of the literature is given in Section 2, study hypotheses are presented in Section 3, the variables and techniques used are described in Section 4, the empirical results are shown in Section 5, and a discussion of the findings is presented in Section 6.

2. Literature Review

2.1. The Effect of CETS on Air Quality

As a market-based tool for reducing emissions, carbon-emission trading is not only regarded as an important means to reduce greenhouse gas emissions, but also gradually shows its potential synergistic effect on improving air quality. In recent years, many studies have explored the impact of China's carbon-emission trading pilot policy on air quality through an analysis of the policy, covering a variety of research methods and regional heterogeneity. The results show that the carbon-emission trading policy has a significant improvement on air quality, but there are also several challenges.

Multiple studies have shown that carbon-emission trading policies have a significant effect on improving air quality. (Liu et al., 2021) found that the pilot policy of carbon trading reduced $PM_{2.5}$ concentration by 4.8% based on the DID model, especially in summer [8]. Similarly, (Lu et al., 2024) found that the pilot policy of carbon trading effectively reduced urban environmental pollution, especially in central and western cities, based on DID model research [9]. (Weng et al., 2022) used a fixed-effect model to analyze the significant emission reduction effect of carbon trading pilot policies on pollutants such as $PM_{2.5}$ and PM_{10}, especially during the quota compliance period [10]. The quasi-natural experiment study of (Sun et al., 2024) verified the role of carbon trading policies in improving air quality in pilot cities through the PSM-DID model [11]. Meanwhile, (Zhang et al., 2022) pointed out that carbon-emission trading policies can effectively limit the carbon-emission level in pilot areas and promote energy efficiency in pilot areas [12]. The vast majority of research data is simply based on provincial levels, while (Zhang et al., 2019) analyzed data at the industrial sub-sector level in various provinces in China to explore whether China's pilot carbon-emission trading system, ETS, has promoted carbon-emission reduction. The results showed that compared to non-covered sub-sectors, after the launch of the ETS pilot, the industries affected by the pilot significantly reduced carbon emissions [13]. Some scholars also use prefecture-level city data, such as (Li et al., 2023), who used panel data from 285 prefecture-level cities in China from 2005 to 2018 and found that carbon-emission trading schemes can effectively reduce urban carbon emissions, as well as $PM_{2.5}$ and SO_2 emissions [14]. (Shi et al., 2022) also used panel data from prefecture-level cities to draw the same conclusion [15]. These research results consistently indicate that carbon-emission trading policies are an effective tool that can promote the improvement of air quality.

In terms of exploring the theoretical mechanism of the impact of carbon-emission trading policies on air quality, the research of (Li et al., 2021) emphasizes the core mechanism of China's carbon market pilot: effectively reducing air pollution by reducing energy consumption, promoting technological progress, and promoting the optimization and upgrading of industrial structure [16]. In addition, the research of (Liu et al., 2023) shows that the carbon-emission trading policy achieves the coordinated control of carbon dioxide emissions and air pollutant emissions by improving the green production capacity of pilot areas, reducing regional industrial output, and promoting the upgrading of industrial structure [17]. These findings reveal the multiple pathways through which carbon-emission trading policies can promote environmental quality improvement.

Although carbon trading policies have made progress in improving air quality, they still face several challenges. (Tan and Wang, 2017) pointed out that the performance of

China's carbon trading market is poor, and the main reasons for this include insufficient legal binding, market segmentation, excessive quotas, and lack of investment [18]. (Lin and Huang, 2022) further emphasized that due to the incomplete maturity of market mechanisms, carbon trading policies rely on government intervention in actual implementation, which limits the potential of market-based means for emission reduction [19]. The research of (Li et al., 2023) reveals that the pilot carbon market has insufficient liquidity, which not only fails to achieve efficiency, but also increases unnecessary costs [20]. In addition, (Almond and Zhang, 2021) found through a meteorological station data analysis that although carbon trading policies have improved air quality in pilot areas, their effect is limited, and there is a phenomenon of pollution leaking into non-pilot areas [21]. (Shen et al., 2024) also found that there is a phenomenon of "carbon leakage", and the pilot policy of carbon trading has led to domestic pollution transfer, especially in East China, where some companies transfer pollution to other regions to avoid emission restrictions [22]. These challenges indicate that carbon trading policies need to address legal, market, and regulatory issues in practical operations to ensure their effectiveness and fairness. At the same time, further research and policy design improvements are needed to reduce carbon leakage and ensure that carbon trading policies can truly promote air quality improvement nationwide.

In the analysis of the impact of CETS on air quality, while the majority of studies suggest that CETS has a positive effect on air quality improvement, there is a lack of a specific analysis on the changes in air quality components. Although the research covers a variety of regions, an in-depth analysis of the specific environmental, economic, and social structures of different areas remains insufficient. This implies that the specific effects of CETS in different regions may be generalized, failing to reveal its mechanisms of action and outcomes in specific contexts.

2.2. Impact of CETS on Green Technology Innovation

CETS encourages enterprises to upgrade their industries and promote green development by establishing a carbon-emission trading mechanism. CETS has greatly increased the degree of green technology innovation within businesses. Studies reveal a notable degree of geographical variability in the promotional effect (Fengxiu et al., 2022) [23]. Higher degrees of liberalization, more intellectual property protection, and stronger human capital all contribute to the policy effect (Weiming et al., 2022) [24]. Higher-administrative-level cities as well as the eastern and western regions exhibit it more strongly, but lower-administrative-level cities and the central area do not. Significant enterprise variability in the promotional effect is also revealed by studies. There are many who contend that state-owned businesses, big businesses, and "mature" businesses are more affected by policy. According to Xiaoqi et al. (2022) [25], there is no discernible impact on state-owned and high-tech firms from the policy effect on green technology innovation in non-state-owned and non-high-tech enterprises. Regarding mechanisms, Yan et al. (2023) [26] think that government intervention has a negative regulatory effect, liberalization and financial development level positively regulate CETS's green technology innovation, and investments in human capital and scientific and technological support play a partial mediating role. The benefits of CETS can also be increased by a lower percentage of state-owned businesses and higher total factor productivity. Research also reveals that the effect of CETS on company-based green technology innovation lags behind policy changes (Zhong et al., 2024 [27]; Weiming L et al., 2022 [24]).

Although current research has demonstrated the impact of CETS on green technology innovation, there is still a lack of policy heterogeneity analysis regarding its geographical distribution differences, which necessitates more in-depth studies tailored to different regions.

2.3. Impact of CETS on Industrial Upgrading

Driven by CETS, industrial upgrading has accelerated the pace of green technology innovation, providing enterprises with the impetus to transition to low-carbon and en-

vironmentally friendly production models. The majority of research indicates that CETS significantly improves industrial upgrading, and that CETS can ameliorate the U-shaped relationship between industrial upgrading and green development both in the short- and long term. Furthermore, the concurrent implementation of CETS with industrial upgrading can result in a super bonus of "one plus one is greater than two" (Jiang et al., 2024) [28]. Industrial upgrading plays a mediating role in the impact of CETS on carbon emissions. Larger cities and non-resource-based cities exhibit more notable effects in terms of regional heterogeneity. Nonetheless, some research contends that CETS actually accelerates the movement of companies from policy pilot areas to non-pilot areas, rather than fostering the upgrading of industrial structure (Yan et al., 2024) [29].

The mediating role of industrial upgrading in the impact of CETS on carbon emissions needs to be further verified through rigorous statistical methods and long-term data. Current research may lack an in-depth analysis and the long-term tracking of this mediating effect.

3. Research Hypotheses

By placing a price on carbon emissions, CETS encourages businesses to take action to lower their emissions of greenhouse gasses. Businesses are encouraged to look for greener energy sources and industrial techniques when they are forced to pay for their carbon emissions, which lowers the emission of greenhouse gasses like carbon dioxide. Reducing greenhouse gas emissions improves air quality in addition to aiding in the mitigation of global climate change. For example, since some particles are chemically connected to greenhouse gasses like carbon dioxide, reducing carbon dioxide emissions can also indirectly lower the creation of particulate matter in the atmosphere.

CETS can reduce carbon emissions, and the reduction of carbon emissions is achieved through pathways such as green technology innovation, industrial upgrading, and reduced energy intensity. By reducing the use of fossil fuels, this procedure will improve overall air quality by having a knock-on effect that lowers emissions of other air pollutants like sulfur dioxide and fine particulate matter ($PM_{2.5}$). Thus, the first hypothesis is put forth in this paper:

Hypothesis 1. *CETS can improve the air quality of various cities in China.*

In the realm of corporate technological innovation, CETS stimulates enterprises to engage in technological innovation to enhance energy efficiency and reduce carbon emissions. New technologies and processes can not only lower production costs for businesses but also decrease the emission of pollutants. For instance, the development of more efficient combustion technologies can reduce the pollutant content in exhaust gasses; the research and development of new types of emission reduction equipment can effectively remove harmful substances from the atmosphere. The diffusion effect of technological innovation can also drive the upgrading of the entire industry, further promoting the improvement of air quality.

When it comes to improving the industrial structure, CETS may force industries that use a lot of energy and produce a lot of pollution to change, adapt, or switch to low-emission sectors. Because they cannot afford the high costs associated with carbon emissions, some highly polluting businesses may eventually be forced out of the market, but environmentally friendly businesses will have more prospects for growth. By streamlining the industrial structure, air quality can be enhanced and total pollutant emissions can be decreased. Meanwhile, the emergence of the new green industries will also inject fresh energy into the expansion of the economy. Consequently, the second hypothesis is put forth in this paper:

Hypothesis 2. *The improvement of air quality by CETS is realized through two channels: enterprise green technology innovation and industrial structure upgrading.*

In terms of economic development, the eastern regions of China are economically advanced with a diversified industry, intense corporate competition, and high operating costs. Consequently, CETS significantly impacts enterprise costs and profitability, making businesses in these regions more sensitive to the policy. Particularly, export-oriented enterprises in the eastern regions are likely to actively respond to CETS to meet international environmental standards and avoid losing market share. The central regions of China are experiencing rapid economic development and are in the process of upgrading its industrial structure. The sensitivity of enterprises to the carbon-emission trading policy is moderate; some heavy industrial enterprises have begun technological transformations driven by the policy, but they have limited resources and capabilities. The western regions, which are relatively less economically developed, are dominated by resource extraction industries. Enterprises in these regions have limited profitability and a low sensitivity to cost changes, resulting in a lower level of attention to the carbon-emission trading policy. Regarding energy resources, the eastern regions rely heavily on external energy inputs, which are costly. The implementation of the CETS may further increase energy costs, making enterprises in these regions sensitive to the policy. The central regions, though rich in energy resources, have low energy utilization efficiency. The policy may encourage energy-saving modifications, but the urgency is not as high as in the eastern regions. The western regions, abundant in energy resources, lag in development technology and have low energy utilization efficiency, leading to a lower sensitivity of enterprises to the policy. In terms of policy support and regulatory intensity, local governments in the eastern regions have a strong sense of environmental protection, provide substantial support, introduce complementary policies, and strengthen regulation, thereby increasing the sensitivity of enterprises to the policy. Governments in the central regions have improved their understanding of the policy, but their support and regulatory efforts require enhancement. Governments in the western regions have limited fiscal capacity, offer less support, and have weaker regulatory capabilities, resulting in the lower sensitivity of enterprises to the policy and affecting the effectiveness of policy implementation. Therefore, this paper proposes the third hypothesis:

Hypothesis 3. *The effects of CETS vary greatly between China's regions.*

The mechanism of CETS on improving air quality is shown in Figure 1.

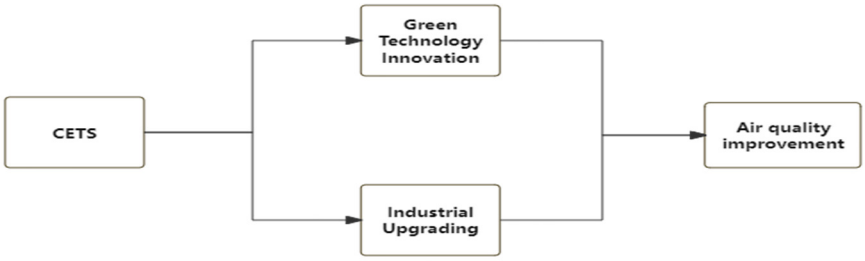


Figure 1. The impact mechanism of CETS on air quality.

4. Variables and Models

4.1. Data Sources

The subject of this study is 284 cities in China, with the research timeframe spanning from 2008 to 2021. The CETS pilot cities and their corresponding pilot times are sourced from public news reports. Air quality data are derived from the statistical yearbooks of each city, environmental statistics yearbooks, and the China National Environmental Monitoring Center. Other city-related data, such as economic development level, urbanization level, market size, environmental regulation, green patent counts, and industrial structure, are all obtained from the city's statistical yearbooks.

4.2. The Definitions of the Variables

In this paper, the dependent variable is air quality. Referring to the research of Wang and Yang (2019) [30] and Al-Janabi et al. (2021) [31], we comprehensively calculate air quality based on $PM_{2.5}$, SO_2, and nitrogen oxides, and use the entropy method to obtain the air quality index. The $PM_{2.5}$ concentration is defined as the presence of particulate matter in the atmosphere with a diameter of 2.5 μm or smaller. The $PM_{2.5}$ concentration is one of the important indicators to measure air quality; the higher the concentration, the more harmful substances are present in the air, posing a greater threat to human health. SO_2 is a colorless, pungent gas primarily originating from the combustion of sulfur-containing fuels. SO_2 concentration is one of the key parameters for measuring the degree of air pollution; its reduction signifies a decrease in sulfur dioxide content in the air. High concentrations of SO_2 are not only harmful to human health but can also lead to acid rain, causing damage to the ecological environment.

Next, we will show the changes in relevant situations in China from 2008 to 2021, as shown in Figure 2.

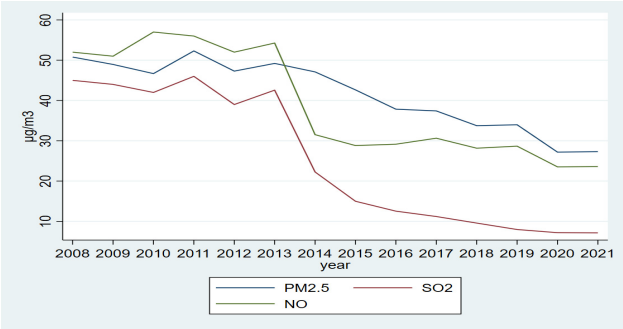


Figure 2. The change graph of $PM_{2.5}$, SO_2, and NO in CETS pilot provinces from 2008 to 2021.

Figure 2 depicts the changing values of $PM_{2.5}$, SO_2, and NO in CETS pilot provinces from 2008 to 2021. Judging from the graphs, since the formal implementation of China's carbon-emission trading rights in 2014, the emissions of $PM_{2.5}$, SO_2 and NO have decreased significantly. Among them, the emissions of SO_2 and NO have even shown a cliff-like decline.

The control variables mainly include the level of economic development, the level of urbanization, the market size, and environmental regulation. Referring to the research of Yang (2018) [32], Han et al. (2014) [33], Cheng (2022) [34], and Zou et al. (2023) [35], economic development drives industrial prosperity and energy consumption; more resources dedicated to greening and ecological protection are beneficial for improving air quality. However, it also brings air pollution issues such as industrial exhaust emissions and fossil fuel combustion. The advancement of the urbanization process leads to the aggregation and expansion of urban populations, exacerbating the deterioration of air quality, especially with the increase in motor vehicle emissions and industrial activities that have a significant negative impact on air quality. The expansion of market size is often accompanied by an increase in industrialization and commercial activities, which may increase the emission of air pollutants, thereby affecting air quality. However, the expansion of the market size also provides more opportunities for the promotion of environmental protection technologies and clean energy, indirectly helping to improve air quality. The implementation of environmental regulation policies aims to reduce corporate pollution emissions and improve air quality, with their effectiveness depending on the level of support and cooperation from the government, enterprises, and citizens. Effective environmental regulation can significantly alleviate urban air pollution problems.

For mechanism testing, the main variables used are the number of green patents and industrial structure upgrading.

The symbols and calculations of the variables are shown in Table 1.

Table 1. The definitions of the variables.

Variable Name	Variable Symbol	Variable Calculation
Air quality composite index	AQ	From the entropy method
nitrogen oxide	NO_x	NO_x(ppm)
The concentration of $PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$ ($\mu g/m^3$)
The concentration of SO_2	SO_2	SO_2 (ppm)
The level of economic development	GDP	The per capita regional GDP (10,000 yuan)
The level of urbanization	UR	The permanent urban population/The total permanent population (%)
Market scale	MS	ln (total amount of social consumer products sold at retail) (billion yuan)
Environmental regulation	ER	Overall rate of general industrial solid waste consumption (%)
The number of green patents	GP	The total amount of green patent applications(number of items)
Industrial structure	IS	Tertiary industry added value/Secondary industry added value (%)

4.3. Model Introduction

This paper draws on the research methodology of Haibo et al., 2023 [36] and uses a time-varying difference-in-differences (DID) model to investigate the effects of the carbon-emission trading pilot policy on air quality, because the policy begins at different times in each of the pilot cities. When dealing with evenly applied policy timings, the conventional DID technique may run into problems with confusing treatment effects. This problem is better mitigated and the model's robustness is increased by the time-varying DID model, which permits the execution of policies at various times in time. The model is configured in the following way:

$$\mathbf{AQ_{it}} = \alpha_0 + \alpha_1 \mathbf{Treat_{it}} \times \mathbf{Time_{it}} + \beta \mathbf{X_{it}} + \mathbf{u_{it}} + \lambda_{\mathbf{it}} + \varepsilon_{\mathbf{it}} \quad (1)$$

In the model, AQ_{it} represents the air quality level of city i at time t, expressed using a composite index. $Treat_{it} \times Time_{it}$ denotes the implementation of policies. $Treat_{it}$ indicates whether the city is a pilot city; it is set to 1 if the city is a pilot and 0 otherwise. $Time_{it}$ signifies whether the city initiates the pilot program at time t; it is set to 1 if the pilot program commences and 0 otherwise. X_{it} represents control variables, namely market size, urbanization level, economic development level, and environmental control level, with their measurement methods and concepts provided earlier. Among them, u_{it} and λ_{it} denote time effects and individual fixed effects, respectively.

5. Empirical Analysis and Results

5.1. Descriptive Statistics

Table 2 presents the results of the descriptive statistics for the variables.

Table 2. Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
AQ	3976	3.689	0.375	1.16	4.691
NO_x	3976	6.19	7.14	0.01	8.76
$PM_{2.5}$	3976	42.751	15.538	3.191	108.955
SO_2	3976	3.936	4.977	0.01	9.95
GDP	3976	10.608	0.654	4.595	13.056
UR	3976	0.541	0.159	0.131	1.001
MS	3976	15.445	1.109	5.472	19.013
ER	3976	79.029	23.378	0.24	156.45

The standard deviations for $PM_{2.5}$, SO_2, and NO_x across the cities are 15.538 $\mu g/m^3$, 4.977 ppm, and 7.14 ppm, respectively, demonstrating significant variation among the cities. This paper examines the impact of the carbon-emission trading system (CETS) on the air quality of various cities, which holds practical significance.

5.2. Empirical Results

Table 3 reports the baseline regression results.

Table 3. Benchmark regression.

Variable	(1)	(2)	(3)	(4)	(5)
CETS	−0.060 ***	−0.056 ***	−0.056 ***	−0.056 ***	−0.057 ***
	(−8.97)	(−9.27)	(−9.05)	(−9.85)	(−8.49)
GDP		−0.066 ***	−0.064 ***	−0.057 ***	−0.057 ***
		(−8.31)	(−9.17)	(−7.63)	(−7.95)
UR			−0.055 *	−0.064 **	−0.057 *
			(−1.86)	(−2.86)	(−1.92)
MS				−0.015 ***	−0.014 **
				(−5.57)	−2.59
ER					−0.001 ***
					(−4.7)
Constant	3.865 ***	4.517 ***	4.536 ***	4.690 ***	4.709 ***
	(841.5)	(64.14)	(76.32)	(40.62)	(53.37)
Urban-fixed	Yes	Yes	Yes	Yes	Yes
Time-fixed	Yes	Yes	Yes	Yes	Yes
Observation	3976	3976	3976	3976	3976
R-squared	0.847	0.851	0.854	0.855	0.856

Note: *, **, and *** indicate significance at the levels of 10%, 5%, and 1%, respectively.

The results in the fifth column show that, at a significance level of 1%, the carbon-emission trading pilot policy has reduced air pollution by 0.057 units and improved air quality. The carbon-emission trading pilot policy improves air quality by creating a market mechanism that puts a price on carbon. This encourages industries to reduce their carbon emissions, as it becomes economically advantageous to do so. By limiting the amount of greenhouse gasses released into the atmosphere, the policy indirectly mitigates air pollution, leading to cleaner air and better respiratory health for communities. As firms adopt cleaner technologies and practices, overall air quality improves, benefiting both the environment and public health. Moreover, the level of economic development, the level of urbanization, market size, and environmental regulation all have significant negative impacts on air quality.

Table 4 displays the further regression outcomes.

It illustrates the policy's influence on $PM_{2.5}$ in columns (1) and (2), which account for city-specific and temporal dynamics, with column (2) also incorporating additional controls. The analysis reveals that the carbon-emission trading system (CETS) significantly contributes to the reduction of $PM_{2.5}$ levels, with a decrease of 1.979 units at the 5% significance level without controls, and 2.548 units at the 10% level with controls, indicating an effective curb on $PM_{2.5}$ emissions.

Columns (3) and (4) examine the policy's impact on SO_2 concentrations, both adjusted for city and time factors, with column (4) integrating control variables. The results demonstrate a significant reduction in SO_2 emissions attributable to CETS, with a 0.207 unit decrease at the 1% significance level without controls, and a 0.180 unit decrease with controls, suggesting a substantial reduction in SO_2 emissions.

Columns (5) and (6) assess the effect of CETS on NO_x concentrations, adjusted for individual and temporal variables, and column (6) includes control variables. The findings suggest that CETS caused a significant decrease in NO_x concentration by 0.295 units at the 1% significance level and 0.132 units in the absence of control, highlighting the improvement in air quality with this policy.

Table 4. Further regression.

Variable	$PM_{2.5}$		SO_2		NO_x	
	(1)	(2)	(3)	(4)	(5)	(6)
CETS	−1.979 **	−2.548 ***				
	(−2.18)	(−2.84)				
			−0.207 ***	−0.180 ***		
			(−4.04)	(−3.42)		
					−0.132 ***	−0.295 ***
					(−7.56)	(−4.13)
GDP		−2.158 ***		−0.049		−1.385 ***
		(−5.17)		(−0.86)		(−4.99)
UR		−6.832 ***		0.529		−0.998
		(−4.22)		(2.33)		(−0.76)
MS		−0.764 **		0.052		−0.006
		(−2.57)		(1.28)		(−1.73)
ER		−0.016 ***		−0.001		−0.332 ***
		(−6.72)		(−1.33)		(−6.96)
Constant	49.896 ***	87.098 ***	1.447 ***	1.013	1.866 ***	1.276 ***
	(191.78)	(17.79)	(42.32)	(1.51)	(31.63)	(9.60)
Urban-fixed	Yes	Yes	Yes	Yes	Yes	Yes
Time-fixed	Yes	Yes	Yes	Yes	Yes	Yes
Observation	3976	3976	3976	3976	3976	3976
R-squared	0.750	0.760	0.706	0.707	0.732	0.735

Note: ** and *** indicate significance at the levels of 5% and 1%, respectively.

5.3. Channel Analysis

Regarding how CETS affects corporate innovation in green technology, strict emission standards and environmental regulations put pressure on businesses to find more eco-friendly technologies and production methods in order to comply with the law. Research has found that CETS significantly enhances the level of corporate green technology innovation, and this promotional effect exhibits significant regional heterogeneity.

Corporate green technology innovation has the ability to improve air quality by reducing emissions of pollutants, increasing energy efficiency, and reducing energy usage. New energy-saving technology, for example, can reduce the energy used in transportation and industrial production, which in turn lowers the emissions of pollutants like sulfur dioxide and carbon dioxide. Conversely, innovations in green technology can result in the creation of products and production methods that are more ecologically friendly. For instance, promoting green products like new energy vehicles can reduce environmental pollution from transportation, and using new eco-friendly materials and clean production technologies can reduce pollutant emissions in the industrial production process. Air quality is positively impacted by green technology innovation, according to research (Zhongqingyang et al., 2023 [37]; Ziwen et al., 2023 [38]).

This paper refers to Haibo et al., 2023 [36] for the following model study. Model 2, used in this paper to examine how CETS affects innovation in green technology, is structured as follows:

$$GP_{it} = \gamma_0 + \gamma_1 Treat_{it} \times Time_{it} + u_{it} + \lambda_{it} + \varepsilon_{it} \quad (2)$$

In terms of the impact of CETS on industry modernization, policymakers can develop plans and strategies that promote the development of new industries and advanced manufacturing while restricting the expansion of highly polluting and energy-intensive industries. Studies have indicated that CETS exerts a markedly positive effect on the upgrading of industrial structures.

The enhancement of industrial structures is pivotal for air quality improvement, as it diminishes the dominance of heavily polluting sectors and bolsters the presence of industries that are less polluting and confer higher economic value. In the transition towards a modernized industrial framework, industries noted for high energy consumption and

pollution, such as steel and chemicals, are incrementally overshadowed by burgeoning sectors in energy conservation, environmental protection, and technology—industries that are more circumspect in their emission profiles, thus contributing to air quality enhancement. Concurrently, this shift fosters a transformation in economic growth paradigms, migrating from an expansionary to a sustainable model. Within this sustainable model, there is an increased focus on innovation and the optimization of resource use, which in turn mitigates environmental degradation. Furthermore, the upgrading of industrial structures can catalyze the growth of ancillary industries, creating a green industrial ecosystem. The expansion of energy-saving and environmental protection sectors, for example, can invigorate associated fields like new energy and new materials, leading to a collective enhancement in resource efficiency and a reduction in emissions, which are conducive to better air quality. Scholars contend that such an industrial evolution can effectively curb $PM_{2.5}$ emissions and refine overall air quality (Haibo et al., 2023) [36].

This paper refers to Haibo et al., 2023 [36] for the following model study. This study examines the effect of CETS on improving industrial structure using model 3 as a guide:

$$IS_{it} = \gamma_0 + \gamma_1 Treat_{it} \times Time_{it} + u_{it} + \lambda_{it} + \varepsilon_{it} \quad (3)$$

Table 5 delineates the outcomes of the mechanism analysis.

Table 5. Mechanism test.

Variable	The Number of Green Patent Applications (7)	Industrial Structure Upgrading (8)
CETS	471.650 ***	0.125 *
	(5.37)	(2.56)
Constant	93.403	0.007 ***
	(1.59)	(55.05)
Urban-fixed	Yes	Yes
Time-fixed	Yes	Yes
Observation	3976	3976
R-squared	0.144	0.566

Note: * and *** indicate significance at the levels of 10% and 1%, respectively.

It juxtaposes the policy's influence on green patent filings against the evolution of industrial structures in columns (7) and (8), respectively, with adjustments for both entity-specific and temporal variables. The core regression findings underscore the substantial influence of CETS on enhancing the volume of green patents and the modernization of industry frameworks.

At the 1% significance level, the policy will increase the number of green technology patent applications by 471.650, suggesting that CETS promotes corporate green technological innovation. At the 10% significance level, the policy will increase the advancement of industrial structure by 0.125 units, indicating that CETS fosters industrial upgrading.

5.4. Robustness Test

The robustness test of the regression results takes up the majority of this section. This paper mainly uses two approaches in this regard. The parallel trend test is one. The placebo test is the alternative.

5.4.1. Parallel Trend Test

The basic regression analysis creates a relationship between the independent and dependent variables, but it is prone to errors, such as possible internal causation. In order to reduce the impact of internal causation on the regression results, the difference-in-differences (DID) method is utilized in this work to validate the results. Eliminating the influence of variables other than carbon-emission trading rights, including the macroe-

conomic environment, is the goal. Selection bias may arise while employing the DID approach, because it necessitates the manual selection of the treatment and control groups. To avoid selection bias, this paper refers to the parallel trend test by Meng X et al. (2018) [39] and adopts an event study analysis method for testing, with the econometric equation shown as follows:

$$Air_{it} = \alpha + \sum_{T=-4,T\neq-1}^{6} \beta_T 1(year = T) \times Treat_{it} \times Time_{it} + \gamma C_f \times \lambda_t + \lambda_f + u_{it} + \lambda_{it} + \varepsilon_{it} \quad (4)$$

In model 4, a newly defined dummy variable for the year is denoted as 1 (year = T). If the year is the Tth year, it takes a value of 1; otherwise, it is 0. Specifically, the year when a city first implements CETS is set as period 0 (T = 0). There are a total of 10 dummy variables ranging from T = −4 to T = 6. Here, T = −1 serves as the base period, and the dummy variable for this year is omitted. The meanings of the other variables are in line with the baseline regression equation. The coefficient, which shows the difference in air quality between the treatment and control groups in the Tth year, is the primary emphasis. Figure 3 below shows the results of the parallel trend test.

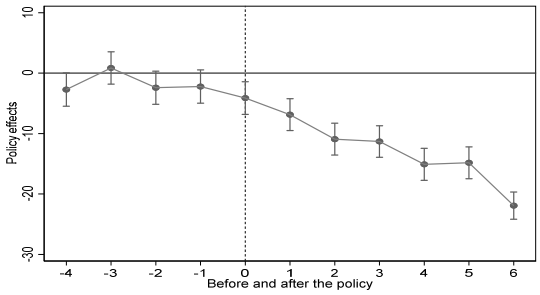


Figure 3. Parallel trend test.

The findings indicate that the zero-axis and the confidence interval of θ intersect prior to the policy's adoption. Nevertheless, following the policy's execution, there is a considerable deviation of the confidence interval of θ from the zero-axis. This suggests that the shift in air quality has been significantly influenced by CETS. More specifically, it has enhanced the number of days with exceptional and good air quality while decreasing $PM_{2.5}$ and SO_2 emissions.

5.4.2. Placebo Test

This research uses the Arkhangelsky (2021) placebo test as a model to examine if missing variables impact the regression findings [40]. It randomly selects cities as pilot cities and, based on the number of pilot cities in a given year, randomly selects the same number of cities to construct their dummy variables. Then, it uses the baseline regression model to repeat the regression for each of the three explanatory variables 500 times. Figure 4 below shows the results of the placebo test.

In Figure 4, the red dots represent the estimated coefficients obtained from the placebo test. The red curve denotes the kernel density estimation of these estimated coefficients, illustrating the distribution of the coefficients derived from the placebo test.

The findings show that the regression coefficients obtained using random samples in the three equations are primarily dispersed around zero. Furthermore, compared to the majority of the simulated values, the basic regression coefficients are smaller. In terms of *p*-values, a certain number of results in different equations are smaller than the corresponding basic regression coefficients, leading to the conclusion that the probability of the simulated results being correct in different equations is 95.3%, 95.4%, and 95.9%, respectively. This indicates that the conclusion that CETS improves air quality is not affected by missing variables with a probability of at least 95%.

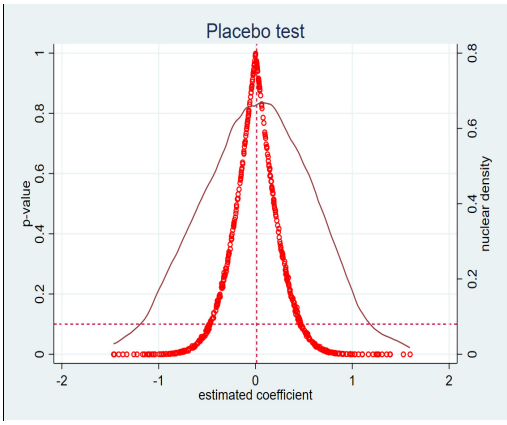


Figure 4. Placebo test.

5.5. Heterogeneity Analysis

A heterogeneity test based on China's regional divides will be conducted in this study. China is split into three regions: east, middle, and west, taking into account aspects like population, resources, and physical location. This section will look at the different ways that CETS have affected each of these areas.

Provinces and cities including Beijing, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, and Hainan are located in the eastern part of the country. The majority of these provinces are found in eastern China's coastal regions, which have more developed economies, high levels of openness to the outside world, convenient transportation, modern industries, and higher energy usage. Provinces like Shanxi, Henan, Anhui, Hubei, Jiangxi, and Hunan are located in the central area.

The central region of China is a vital source of raw materials and energy for the country, as well as a base for the production of high-tech industries and modern equipment. It also acts as a bridge between the country's southern and northern regions and its eastern and western regions. Provinces and autonomous areas including Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang are included in the western region. Despite having a large territory and an abundance of resources, the western region's economic development is comparatively slow, and it uses less energy overall.

The benchmark regression result is shown in Table 6.

Table 6. Heterogeneity test.

Variable	$PM_{2.5}$			SO_2			NO_x		
	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
CETS	−2.221 ***	−9.561 ***	−14.103 ***						
	(−2.18)	(−12.49)	(−5.97)						
				−0.163 ***	−0.098	−0.521			
				(−2.66)	(−0.93)	(−1.60)			
							−0.157 ***	−0.169 ***	−0.332
							(−4.16)	(−6.24)	(−0.26)
Constant	49.777 ***	49.777 ***	49.777 ***	1.448 ***	1.448 ***	1.448 ***	243.951 ***	243.951 ***	243.951 ***
	(202.23)	(202.23)	(202.23)	(42.39)	(42.39)	(42.39)	(73.06)	(73.06)	(73.06)
Urban-fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time-fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observation	3976	3976	3976	3976	3976	3976	3976	3976	3976
R-squared	0.761	0.761	0.761	0.706	0.706	0.706	0.139	0.139	0.139

Note: *** indicate significance at the levels of 1%.

The policy's effects on $PM_{2.5}$, SO_2, and NO_x are shown in columns (1), (3), and (5), respectively. All columns have been adjusted for individual and temporal fixed effects.

Additional control variables are incorporated in columns (2), (4), and (6). According to the baseline regression analysis, CETS plays a substantial role in lowering SO_2, $PM_{2.5}$ and NO_x.

In the eastern region, CETS helps reduce the concentration of various air pollutants. However, in the central region, this policy has an insufficient impact on reducing sulfur dioxide emissions, and in the western region, it has no significant impact on mitigating nitrogen oxide emissions. Regional differences in policy effectiveness may stem from differences in industrialization levels, energy consumption patterns, and environmental regulations. To enhance the national impact of this policy, tailored strategies that take into account regional characteristics and emission sources should be developed, while strengthening enforcement and monitoring mechanisms.

6. Conclusions and Discussion

6.1. Conclusions

Although air pollution poses a threat to the sustainable development of cities, the green development effects caused by various policies have alleviated this problem. Building on the existing literature, this paper delves deeper into the analysis of changes in air quality components and their specific regional contexts, adopting a time-varying difference-in-differences model. Taking the CETS pilot as the distinction and using the annual air quality data ($PM_{2.5}$, SO_2, and NO_x) of 284 cities in China from 2008 to 2021, the following results are obtained:

CETS has significantly improved air quality in Chinese prefecture-level cities by reducing overall pollutant concentrations, as evidenced by decreases of 2.548 units in $PM_{2.5}$, 0.180 units in SO_2, and 0.295 units in NO_x when controlling for variables. This policy not only enhances air quality but also fosters corporate green development and sustainable capacities through industrial upgrading and innovation. Regional disparities are notable; the western region shows a stronger response to $PM_{2.5}$ due to its role in resource extraction and transportation, where CETS is particularly effective. The eastern regions stand out in SO_2 reduction, attributed to its significant consumption of mineral resources and subsequent policy-driven decrease in emissions from processing and production. While NO_x reductions are significant in the eastern and central regions, the western region lags, indicating a need for improved energy extraction practices and enhanced sustainable development.

6.2. Recommendations for Discussion

The zoning of policy is a top priority, as the impact on China's eastern, central, and western regions varies greatly. Green policies need to be tailored to the conditions of each region, avoiding a one-size-fits-all strategy. This includes comprehensive regulation in the central region, strengthening control over sulfur dioxide emissions in the eastern region, and improving policy regulation for $PM_{2.5}$ emissions in the western region. Concurrently, there is a need for better policies that investigate the creation of allocation methods, taking into account the scarcity of carbon-emission rights, balancing efficiency with equity, and considering regional and industry characteristics [41,42]. For instance, increasing the proportion of paid allocations, reducing free quotas for high-energy-consuming and high-emitting enterprises, and rewarding enterprises with advanced technology and effective emission reduction can contribute to sustainable development by improving air quality.

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