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Research on the Impact of the Establishment of Cross-Border E-Commerce Comprehensive Pilot Zones on Environmental Pollution

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Abstract: In the context of the new development paradigm, accelerating global economic integration, and growing emphasis on trade growth and environmental protection, cross-border e-commerce and its comprehensive pilot zones (hereafter referred to as "pilot zones") play a pivotal role in promoting trade and exploring green trade models. This study employs a sample of 287 prefecture-level cities from 2005 to 2022 and utilizes the difference-in-differences (DID) model to examine the impact of pilot zone establishment on sulfur dioxide (SO_2) emissions. The results indicate that the pilot zone policy significantly reduces annual SO_2 emissions in these cities, primarily by enhancing green innovation. Heterogeneity analysis reveals that, in terms of resource endowment, the policy exerts a stronger emission-reduction effect on non-resource-based cities; geographically, it benefits the western region the most; and in terms of urban scale, large cities experience a more pronounced reduction. Based on these findings, this paper proposes targeted development recommendations for resource-based cities, the western region, and small- and medium-sized cities. It also advocates for promoting successful experiences, supporting green technology innovation, and improving the environmental supervision system to achieve coordinated trade and environmental protection, thereby contributing to global green trade transformation.

1. Introduction

Against the backdrop of accelerating global economic integration, trade growth and environmental protection have become focal issues for the international community. While trade growth drives economic development and improves living standards, environmental protection is fundamental to human survival and sustainable development. Achieving synergy between trade growth and environmental protection, thereby realizing a win-win scenario for the economy and ecology, is a critical challenge for nations worldwide. Cross-border e-commerce breaks the geographical and temporal constraints of traditional trade, enabling businesses to directly access global markets, reduce trade costs, improve efficiency, and expand trade channels, thereby boosting international trade. Data show that in 2023, China's cross-border e-commerce import and export volume reached 2.38 trillion yuan, a 15.6% increase, making it a significant driver of economic growth. To foster cross-border e-commerce development, China has established multiple Cross-Border E-Commerce Comprehensive Pilot Zones (hereafter "pilot zones") since 2015.

As a key vehicle for promoting trade digitalization and institutional innovation, pilot zones not only reshape international trade patterns but also serve as policy testbeds for exploring green and low-carbon trade models. By integrating digital technologies, optimizing supply chain management, and standardizing processes, pilot zones enhance trade efficiency while demonstrating potential pathways to reduce environmental pollution. However, existing research predominantly focuses on the economic effects of pilot zones, with insufficient systematic analysis of their environmental improvement mechanisms.

This study selects a sample of 287 prefecture-level cities from 2005 to 2022 and employs the DID model to empirically examine the impact of pilot zone establishment on SO_2 emissions. It explores the theoretical logic and practical pathways for reducing environmental pollution, aiming to provide Chinese insights for global green trade transformation.

2. Policy Background

The establishment of pilot zones is a strategic policy initiative launched by China amid profound changes in the global trade landscape and domestic economic transformation. Following the 2008 global financial crisis, China's traditional foreign trade faced challenges such as fragmented orders, rising costs, and low value-added, rendering the processing trade model unsustainable. In 2015, the State Council approved the first pilot zone in Hangzhou, aiming to reconstruct trade chains through cross-border e-commerce, cultivate an "internet + foreign trade" ecosystem, and address bottlenecks in traditional trade growth.

Table 1: List of Cross-Border E-Commerce Comprehensive Pilot Zones

Year of Establishment	List of Cross-Border E-Commerce Comprehensive Pilot Zones
2015	Hangzhou
2016	Ningbo, Zhengzhou, Tianjin, Shanghai, Chongqing, Hefei, Guangzhou, Shenzhen, Chengdu, Dalian, Qingdao, Suzhou
2018	Beijing, Hohhot, Shenyang, Changchun, Harbin, Nanjing, Nanchang, Wuhan, Changsha, Nanning, Haikou, Guiyang, Kunming, Xi'an, Lanzhou, Xiamen, Tangshan, Wuxi, Weihai, Zhuhai, Dongguan, Yiwu (under Jinhua, Zhejiang)
2019	Shijiazhuang, Taiyuan, Chifeng, Fushun, Hunchun (under Yanbian Korean Autonomous Prefecture, Jilin), Suifenhe (under Mudanjiang), Xuzhou, Nantong, Wenzhou, Shaoxing, Wuhu, Fuzhou, Quanzhou, Ganzhou, Jinan, Yantai, Luoyang, Huangshi, Yueyang, Shantou, Foshan, Luzhou, Haidong, Yinchuan
2020	Xiongan New Area, Datong, Manzhouli (under Hulunbuir), Yingkou, Panjin, Jilin City, Heihe, Changzhou, Lianyungang, Huai'an, Yancheng, Suqian, Huzhou, Jiaxing, Quzhou, Taizhou, Lishui, Anqing, Zhangzhou, Putian, Longyan, Jiujiang, Dongying, Weifang, Linyi, Nanyang, Yichang, Xiangtan, Chenzhou, Meizhou, Huizhou, Zhongshan, Jiangmen, Zhanjiang, Maoming, Zhaoqing, Chongzuo, Sanya, Deyang, Mianyang, Zunyi, Dehong (Dehong Dai and Jingpo Autonomous Prefecture), Yan'an, Tianshui, Xining, Ürümqi
2022	Ordos, Yangzhou, Zhenjiang, Taizhou, Jinhua, Zhoushan, Ma'anshan, Xuancheng, Jingdezhen, Shangrao, Zibo, Rizhao, Xiangyang, Shaoguan, Shanwei, Heyuan, Yangjiang, Qingyuan, Chaozhou, Jieyang, Yunfu, Nanchong, Meishan, Honghe Hani and Yi Autonomous Prefecture, Baoji, Kashgar Prefecture, Alashankou

Subsequently, the State Council approved the second batch of pilot zones in 2016, extending the "six systems + two platforms" model pioneered in Hangzhou. By 2022, China had established 132 pilot zones across 30 provinces, municipalities, and autonomous regions (see Table 1 for details). Under the "dual circulation" strategy, pilot zones are tasked with integrating domestic and international markets, optimizing resource allocation, and facilitating institutional innovations such as streamlined customs clearance and cross-border payment facilitation.

3. Literature Review

Current academic research on Cross-Border E-Commerce Comprehensive Pilot Zones (hereafter referred to as "pilot zones") primarily focuses on their economic effects. From the perspective of urban development, Gao [1] demonstrates that the pilot zone policy contributes approximately a 5% net improvement effect on high-quality urban economic development, with its impact moderated by factors such as infrastructure, internet penetration, and environmental regulations. Liu et al. [2] find that cross-border e-commerce significantly promotes the specialized agglomeration of producer services, facilitating regional industrial upgrading. From a trade perspective, Ma and Guo [3] reveal that pilot zones substantially enhance export extensive margins and volumes by reducing institutional transaction costs, generating "institutional innovation dividends." Peng and Li [4] further highlight that the improvement in informatization levels serves as a critical mediating pathway for pilot zones to boost import and export trade. Zhao et al. [5] argue that pilot zones drive the integration of domestic and foreign trade in pilot cities through innovation effects, foreign investment inflows, and economies of scale, with particularly pronounced effects in less-developed regions. Feng and Deng [6] analyze urban locational advantages, showing that pilot zone policies, synergized with network infrastructure and education expenditure, significantly attract foreign direct investment.

From the perspective of enhancing corporate economic performance, Wang et al. [7], based on data from listed companies, demonstrate that cross-border e-commerce strengthens corporate competitiveness, innovation capacity, and digital infrastructure, thereby significantly improving supply chain resilience. Shi and Yu [8], using patent applications as an indicator, find that pilot zone policies drive corporate innovation through profit growth, technology spillovers, and the integration of manufacturing and services. Li et al. [9] emphasize that pilot zones expand market opportunities, optimize the digital environment, and improve capital allocation, promoting corporate transformation in foundational and digital technology applications.

A few scholars have also explored the green effects of pilot zones. Jiang and Huang [10], using city-level data, show that pilot zone policies significantly enhance urban green technology innovation by strengthening corporate green management capabilities, stimulating green industry entrepreneurship, and optimizing intellectual property protection. Zhang and Zhang [11] further validate at the corporate level that pilot zones improve corporate environmental performance by advancing digital transformation and intelligent manufacturing upgrades, highlighting the "openness promotes green development" pathway. Gao [12], focusing on the "dual carbon" goals, notes that pilot zones suppress regional carbon emissions through the agglomeration effects of producer services, confirming the policy's positive role in low-carbon transition. Xiang et al. [13], using the establishment of pilot zones as a quasi-natural experiment, find that digital trade significantly reduces energy consumption in pilot enterprises through three mechanisms: accelerating digital transformation, enhancing technological innovation capacity, and optimizing the regional business environment. This conclusion aligns with Li and Wang [14], who emphasize that digital trade promotes urban synergy in pollution and carbon reduction through industrial agglomeration and resource allocation optimization.

In summary, while existing studies have extensively examined the economic benefits of pilot zones, research on their environmental effects remains limited, particularly regarding their impact on reducing urban pollution. To address this gap, this study selects a sample of 282 prefecture-level cities from 2010 to 2022 and employs a difference-in-differences (DID) model to empirically assess the impact of pilot zone establishment on sulfur dioxide (SO_2) emissions, providing empirical evidence for green development across different regions.

4. Model Specification and Variable Description

4.1 Model Specification

This study selects 287 prefecture-level cities from 2005 to 2022 as the research sample and treats the approval of Cross-Border E-Commerce Comprehensive Pilot Zones (hereafter "pilot zones") as a quasi-natural experiment. The difference-in-differences (DID) method is employed to analyze the impact of pilot zones on environmental pollution. The baseline regression model is specified as follows:

$$SO2_{it} = \alpha + \beta DID_{it} + \theta X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \qquad (1)$$

Among them, Where represents the sulfur dioxide emissions of city i in year t; $DID_{it}$is a dummy variable indicating whether a cross-border e-commerce comprehensive pilot zone was established, assigned a value of 1 for the year when city i was established as a pilot zone and subsequent years, and 0 otherwise; represents a series of control variables considered in this study. Considering that domestic demand is influenced by numerous factors beyond the control variables incorporated in this study, as well as other unobservable determinants, a two - way fixed effects model is employed for estimation. Here, μ_i and $\lambda_t$denote the city - level and year - level fixed effects, respectively. α is the intercept term; β is the impact coefficient; θ reflects the effect of other control variables on $SO2_{it}$; represents the random disturbance term.

4.2 Variable Selection and Data Sources

4.2.1 Dependent Variable

The annual industrial SO_2 emissions at the prefecture-level city level are selected as the key indicator of urban environmental pollution. SO_2, a typical and major air pollutant, is primarily emitted from stationary sources such as coal combustion in thermal power plants and industrial processes like non-ferrous metal smelting, steel production, chemical synthesis, petroleum refining, and sulfuric acid manufacturing. Compared to other air pollutants, SO_2 emissions originate from relatively concentrated sources, making them a precise and effective metric for quantifying regional environmental pollution, particularly for industrial-sector assessment.

4.2.2 Core Explanatory Variable

The cross-border e-commerce comprehensive pilot zone city (DID) is the interaction term of treat i and time it, where treat i is a variable distinguishing between the treatment group and the control group, identifying whether city i implemented the cross-border e-commerce comprehensive pilot zone policy in year t. The treatment group consists of pilot zone cities, defined as 1; the control group consists of non-pilot cities, defined as 0. timeit represents the dummy variable set before and after the pilot implementation, assigned a value of 0 for years before the pilot implementation and 1 for the year of implementation and subsequent years.

4.2.3 Control Variables

Considering that other factors may affect regional SO2 emissions, this study selects the following control variables:

Economic development level (represented by per capita GDP). Per capita GDP is an important indicator for measuring regional economic development levels and residents' prosperity. As economic development progresses, production technology and pollution control technology may improve, and energy utilization efficiency may increase, thereby affecting SO2 emissions.

Industrial structure level (represented by the proportion of secondary industry value added in GDP). The development of secondary industries, especially industry, requires large amounts of energy, and energy combustion is one of the main sources of SO2 emissions. Different regions have different industrial structures. Regions with higher proportions of secondary industries tend to have larger-scale industrial production, resulting in relatively higher energy consumption and pollutant emissions.

Urbanization rate. During the urbanization process, the concentration of population and economic activities in cities, urban infrastructure construction, industrial development and changes in residents' lifestyles all have impacts on the environment. On one hand, urbanization may lead to more concentrated pollution emissions; on the other hand, cities may also implement stricter environmental supervision and pollution control measures.

Financial development level (year-end balance of various loans from financial institutions/GDP). Financial loans can provide funding support for corporate production operations, technological transformation and innovation. If enterprises obtain more funds for environmental technology upgrades and energy-saving emission reduction projects, SO2 emissions may decrease; conversely, if funds are mainly used to expand high-pollution, high-energy-consumption production scales, emissions may increase.

Fiscal expenditure level (local general budget expenditure/GDP). Local general budget expenditure reflects the government's investment capacity and intensity in public affairs. Among these, expenditures related to environmental protection, such as pollution control facility construction and environmental supervision, will have a direct impact on SO2 emissions. Higher proportions of government fiscal expenditure may mean more funds are used for environmental governance and supervision, thereby reducing SO2 emissions.

4.3 Data Sources

The data used in this study are panel data for 287 Chinese prefecture-level cities from 2005 to 2022 (excluding cities with severe missing data and cities with administrative division changes such as Laiwu and Chaohu). The data come from relevant years of the China City Statistical Yearbook, China Statistical Yearbook on Science and Technology, and China Regional Economic Statistical Yearbook. Table 2 reports the descriptive statistical results of the main variables.

Table 2: Descriptive Statistics of Main Variables

Variable	Observations	Mean	Std. Dev	Min	Median	Max
SO2	5001	4.32	5.37	0.00	2.53	68.32
DID	5364	0.08	0.27	0.00	0.00	1.00
PGDP	5185	4.59	3.46	0.01	3.70	46.77
INDUS	4920	46.23	11.55	8.85	46.47	90.97
URB	5008	0.52	0.17	0.11	0.51	1.00
FIN	5174	0.97	0.62	0.08	0.79	7.45
FIS	5173	0.19	0.13	0.04	0.16	2.35

5. Empirical Analysis

5.1 Baseline Regression Results

The baseline regression results are presented in Table 3. Column (1) shows the regression results without control variables and fixed effects, where the estimated coefficient of DID is negative and statistically significant at the 1% level. Column (2) presents the results including control variables and fixed effects, with the DID coefficient remaining negative and significant at the 1% level. These results clearly demonstrate that the establishment of Cross-Border E-Commerce Comprehensive Pilot Zones has significantly reduced annual sulfur dioxide emissions at the prefecture level.

Table 3: Baseline Regression Results

Variable	(1)	(2)
DID	-2.498***	-2.345***
	(0.272)	(0.298)
PGDP		-0.179***
		(0.049)
INDUS		0.076***
		(0.010)
URB		-1.590
		(0.978)
FIN		0.186
		(0.241)
FIS		2.407*
		(1.351)
_cons	4.519***	2.214***
	(0.044)	(0.855)
Province Fixed Effects	YES	YES
Year Fixed Effects	YES	YES
N	5001	4551
R^2	0.738	0.751

*Note: Values in parentheses are t - values; ***, *, and * indicate significance at the 1%, 5%, and 10% levels respectively. The same below.

5.2 Parallel Trend Test

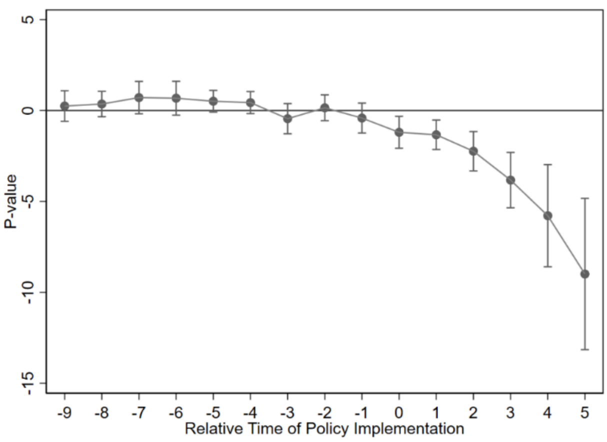

Figure 1: Parallel Trend Test

A crucial prerequisite for evaluating policy effectiveness using the DID model is that the treatment and control groups satisfy the parallel trend assumption, which requires that the trends in sulfur dioxide emissions between the two groups remain consistent prior to the establishment of the Cross-Border E-Commerce Comprehensive Pilot Zones. To verify this assumption, this study employs an event study approach, using the 10th year before the establishment of the pilot zones as the baseline year for parallel trend testing. Figure 1 visually presents the parallel trend test results. At the 95% confidence interval, all estimated coefficients for pre-policy periods are statistically indistinguishable from zero, indicating no significant difference in the trends of urban sulfur dioxide emissions between the treatment and control groups prior to the establishment of the pilot zones. These results confirm that the parallel trend assumption holds.

5.3 Placebo Test

To examine whether the impact of Cross-Border E-Commerce Comprehensive Pilot Zones on urban sulfur dioxide emissions is caused by other random factors, this study conducts a placebo test by randomly assigning treatment and control groups. Following the approach of Hu et al. [15], we randomly select cities from the sample to form the Cross-Border E-Commerce Comprehensive Pilot Zones list as the treatment group, while the remaining cities serve as the control group. Using the newly randomly assigned treatment and control groups, we estimate Model (1) to complete one placebo test. This process is repeated 1,000 times to obtain 1,000 estimated coefficients, and we examine the distribution of these coefficients and their p-values. The results are shown in Figure 2. It can be observed that the estimated coefficients approximately follow a normal distribution within the range of (-0.5, 0.5) and are significantly larger than the baseline regression coefficient. Most estimated p-values are greater than 0.1, indicating that the research conclusions of this paper are robust.

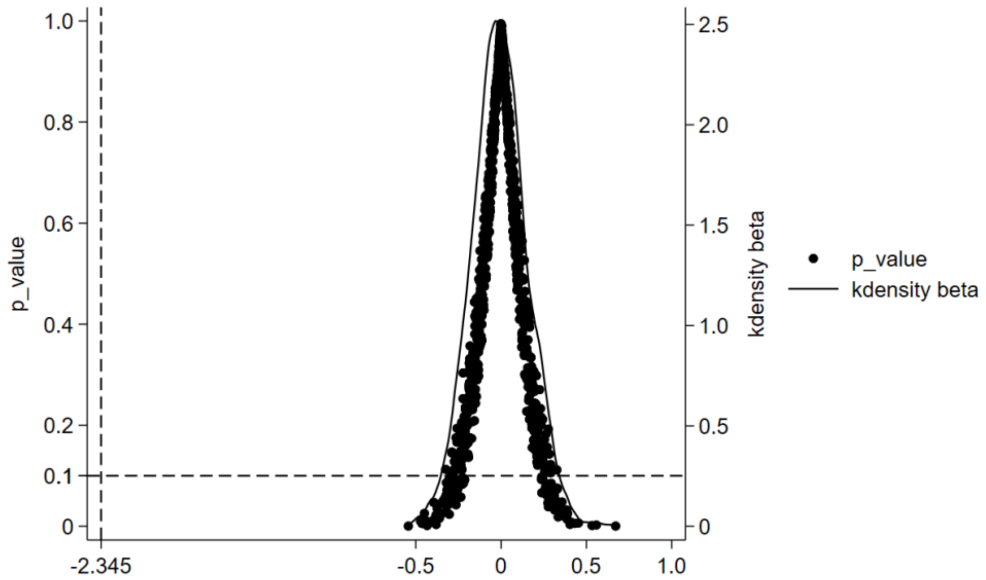

Figure 2: Placebo Test

5.4 Robustness Tests

To ensure the reliability of the baseline regression results, this study employs three approaches for robustness testing: PSM-DID, alternative dependent variables, and subsample regression analysis.

5.4.1 PSM-DID Approach

Considering that the selection of Cross-Border E-Commerce Comprehensive Pilot Zones may not be entirely random and could suffer from self-selection bias, and that inherent differences between treatment and control groups may introduce estimation bias, we address these issues through the PSM-DID method. Following the methodology of Wei et al. [16], we calculate propensity scores using logistic regression (logit) and implement 1:1 nearest neighbor matching within a caliper of 0.05. After obtaining the matched sample, we re-estimate Model (1). The results, presented in Column (1) of Table 4, show a coefficient of -2.290 that remains statistically significant at the 1% level after controlling for urban characteristics. This confirms the significant inhibitory effect of pilot zone establishment on sulfur dioxide emissions and further validates the robustness of our findings.

5.4.2 Alternative Dependent Variables

(1) Given that both sulfur dioxide (SO_2) and carbon dioxide (CO_2) are common pollutants generated during energy consumption - particularly from fossil fuel combustion in traditional industrial production - we replace the dependent variable with city-level CO_2 emissions. As shown in Column (2) of Table 4, the pilot zone policy demonstrates significant inhibitory effects on CO_2 emissions, confirming result robustness.

(2) Sole reliance on total SO_2 emissions may obscure environmental performance assessment, as emission growth could accompany economic expansion while emission intensity improves. To evaluate whether pilot zone development achieves cleaner production alongside economic growth, we adopt SO_2 emission intensity (emissions per unit output) as an alternative metric. The significantly negative coefficient in Column (3) of Table 4 substantiates the robustness of our conclusions.

5.4.3 Subsample Regression Analysis

Table 4: Robustness Tests

Variables	PSM-DID	Alternative Dependent Variables		Subsample Regression Analysis	
	(1)	(2)	(3)	(4)	(5)
DID	-2.290***	302.281***	0.003***	-4.479***	-1.352***
	(0.303)	(68.323)	(0.000)	(0.697)	(0.224)
PGDP	-0.156***	90.351***	0.000***	-0.095**	-0.153***
	(0.046)	(23.004)	(0.000)	(0.043)	(0.045)
INDUS	0.073***	-17.622***	0.000	0.072***	0.060***
	(0.010)	(2.675)	(0.000)	(0.010)	(0.008)
URB	-1.896**	946.323***	-0.004*	-1.046	-2.271**
	(0.963)	(255.765)	(0.002)	(0.921)	(0.940)
FIN	0.125	-33.557	0.002***	0.070	-0.014
	(0.242)	(36.655)	(0.001)	(0.286)	(0.219)
FIS	2.556*	-705.073**	-0.004	3.299**	1.434
	(1.330)	(335.567)	(0.003)	(1.468)	(1.023)
_cons	2.455***	3147.371***	0.004**	2.228***	3.232***
	(0.830)	(240.509)	(0.002)	(0.847)	(0.719)
Province Fixed Effects	YES	YES	YES	YES	YES
Year Fixed Effects	YES	YES	YES	YES	YES
N	4532	4710	4551	3819	4481
R^2	0.754	0.961	0.615	0.818	0.748

(1) Municipalities (Beijing, Tianjin, Shanghai, Chongqing) enjoy higher administrative autonomy

and distinct policy-making capacities compared to ordinary prefecture-level cities. Their unique supporting policies for pilot zone construction might introduce additional impacts on SO_2 emissions. After excluding these four municipalities from our sample, Column (4) of Table 4 continues to show significantly negative policy effects.

(2) The COVID-19 pandemic induced an exceptional economic contraction through mobility restrictions and industrial shutdowns globally, leading to reduced energy consumption and SO_2 emissions unrelated to pilot zone policies. To isolate the policy effect from pandemic interference, we exclude the 2020-2022 period. The results in Column (5) of Table 4 maintain significantly negative coefficients, demonstrating conclusion robustness against external shocks.

All robustness checks collectively confirm that our baseline findings are not artifacts of model specification, variable measurement, or sample composition, thereby strengthening the causal interpretation of the emission reduction effects attributable to pilot zone establishment.

6. Mechanism Analysis

Table 5: Mechanism Test

Variable	(1)
	Green Patent Applications
DID	640.738***
	(56.615)
PGDP	85.462***
	(24.084)
INDUS	-7.088***
	(1.286)
URB	-672.573***
	(157.405)
FIN	130.350***
	(38.229)
FIS	-464.840**
	(227.118)
_cons	394.360***
	(140.543)
Province Fixed Effects	YES
Year Fixed Effects	YES
N	4560
R2	0.663

Green technology innovation accelerates the development and utilization of clean energy sources such as solar, wind, hydro, and biomass power. These clean energy sources produce little to no sulfur dioxide (SO_2) emissions during production and consumption. Additionally, green technology innovation improves energy efficiency, reduces energy waste, and consequently lowers SO_2 emissions associated with energy consumption. Moreover, enterprises adopting clean production processes enabled by green technology innovation can reduce SO_2 emissions at the source. For example, in the chemical industry, some companies have developed and implemented sulfur-free or low-sulfur production techniques, avoiding the use of sulfur-containing raw materials or intermediates, thereby significantly cutting SO_2 emissions. In the paper industry, the adoption of biopulping technology as an alternative to traditional chemical pulping has reduced the use of sulfur-based chemicals, achieving cleaner production. Building on the intuitive explanation of how green technology innovation affects SO_2 emissions, this section conducts a mechanism test by examining the role of green technology innovation. Column (1) of Table 5 presents the regression results, showing that the coefficient for the number of green patent applications is significantly positive. This indicates that the establishment of Cross-Border E-Commerce Comprehensive Pilot Zones enhances green innovation levels, which in turn reduces SO_2 emissions and mitigates environmental pollution.

7. Heterogeneity Analysis

7.1 Resource Endowment

Table 6: Heterogeneity Analysis by Resource Endowment

Variable	(1)	(2)
	Resource-based Cities	Non-resource-based Cities
DID	-1.439**	-3.249***
	(0.623)	(0.336)
PGDP	-0.192*	-0.175***
	(0.100)	(0.057)
INDUS	0.020	0.109***
	(0.015)	(0.013)
URB	-2.355	-1.254
	(1.896)	(0.974)
FIN	-0.250	0.408
	(0.380)	(0.290)
FIS	1.399	2.251
	(1.712)	(2.118)
_cons	6.102***	0.285
	(1.322)	(1.146)
Province Fixed Effects	YES	YES
Year Fixed Effects	YES	YES
N	1803	2714
R2	0.764	0.748

There may be significant differences in resource endowments among different types of cities, which may lead to heterogeneous impacts of the establishment of comprehensive pilot zones on environmental pollution. Therefore, based on the National Sustainable Development Plan for Resource-Based Cities (2013-2020), this paper divides the samples into resource-based cities and non-resource-based cities, and conducts regression analysis respectively. The results are shown in Table 6. It can be found that the effect of establishing cross-border e-commerce comprehensive pilot zones in reducing environmental pollution is significantly stronger in non-resource-based cities than in resource-based cities. The reason lies in that resource-based cities, due to their abundant resources, have formed resource-based industries and development models highly dependent on the processing and production of natural resources, which leads to the region being affected by the "resource curse". Therefore, the policy of establishing comprehensive pilot zones has limited effects on reducing sulfur dioxide emissions in resource-based cities. In contrast, non-resource-based cities have less dependence on natural resources, a more reasonable industrial structure, and more balanced economic development. Therefore, compared with resource-based cities, the establishment of cross-border e-commerce comprehensive pilot zones in non-resource-based cities can more significantly reduce environmental pollution.

7.2 Geographical Location

Due to regional disparities in resource endowments, environmental policies, economic development levels, and technological capabilities across China, the environmental pollution mitigation effects of establishing comprehensive pilot zones may also vary. Therefore, this paper classifies cities into eastern, central, western, and northeastern regions according to Several Opinions of the Central Committee of the Communist Party of China and the State Council on Promoting the Rise of Central China, Implementation Opinions of the State Council on Several Policy Measures for Western Development, and the National Bureau of Statistics' geographical division standards. The pollution reduction effects are tested separately for each region, with results shown in Table 7. Empirical results indicate significant regional heterogeneity in the environmental benefits of cross-border e-commerce pilot zones: The establishment of such zones yields the most pronounced pollution reduction effects in western regions. This can be attributed to their relatively undiversified industrial structures dominated by traditional energy-intensive sectors, creating substantial room for industrial restructuring. Additionally, given the rapid growth of cross-border e-commerce in western regions, emerging business models drive transformative changes in economic activities, leading to high marginal returns in reducing sulfur dioxide emissions.

Table 7: Heterogeneity Analysis by Geographical Location

Variable	(1)	(2)	(3)	(4)
	Eastern	Central	Western	Northeastern
DID	-2.197***	-1.155**	-5.043***	-1.502***
	(0.395)	(0.454)	(1.245)	(0.399)
PGDP	-0.145**	-0.222**	-0.403***	0.581***
	(0.058)	(0.091)	(0.130)	(0.102)
INDUS	0.198***	0.104***	0.051**	-0.015
	(0.025)	(0.018)	(0.021)	(0.014)
URB	-3.561*	5.139***	-1.371	-0.253
	(2.116)	(1.391)	(2.386)	(0.995)
FIN	-0.408	-0.113	2.689***	-0.722***
	(0.597)	(0.414)	(0.699)	(0.235)
FIS	2.936	2.895	-2.721	10.364***
	(2.781)	(3.374)	(1.711)	(1.611)
_cons	-0.954	-3.041**	3.004	0.949
	(2.155)	(1.197)	(1.914)	(1.001)
Province Fixed Effects	YES	YES	YES	YES
Year Fixed Effects	YES	YES	YES	YES
N	1399	1290	1316	511
R2	0.783	0.769	0.744	0.813

7.3 City Size

Cities of different sizes vary significantly in economic structure, resource endowment, and policy responsiveness. Following the Notice of the State Council on Adjusting the Criteria for Determining

City Size (Guo Fa [2014] No. 51), this paper divides Chinese cities into large cities and small/medium-sized cities using the 1 million permanent resident population thresholds in municipal districts. Regression results (Table 8) indicate that the environmental pollution reduction effect of cross-border e-commerce pilot zones is more pronounced in large cities. This divergence can be attributed to the following factors: Large cities typically feature diversified industrial structures with well-developed high-end service sectors (e.g., finance, technology, and information services) alongside traditional manufacturing. During the construction of pilot zones, they are better positioned to foster technology-intensive and knowledge-based cross-border e-commerce activities, driving industrial upgrading and innovation to reduce high-pollution production processes. Conversely, small/medium-sized cities often face challenges such as underdeveloped infrastructure, inefficient logistics, unstable energy supply, and limited resource allocation capabilities. These constraints may lead to higher energy consumption and SO_2 emissions in e-commerce operations, as well as difficulties in adopting green technologies and optimizing resource utilization.

Table 8: Heterogeneity Analysis by City Size

Variable	(1)	(2)
	large cities	small/medium-sized cities
DID	-2.266***	0.571**
	(0.463)	(0.272)
PGDP	-0.036	-0.222***
	(0.046)	(0.085)
INDUS	0.150***	0.043***
	(0.028)	(0.009)
URB	-2.027	-1.161
	(1.754)	(1.138)
FIN	1.092**	0.405
	(0.432)	(0.302)
FIS	-2.281	-0.771
	(2.767)	(1.186)
_cons	0.090	2.741***
	(1.885)	(0.881)
Province Fixed Effects	YES	YES
Year Fixed Effects	YES	YES
N	1642	2875
R2	0.760	0.736

8. Conclusions

Through a study of 287 prefecture-level cities from 2005 to 2022 using a difference-in-differences (DID) model, this paper confirms that the policy of establishing cross-border e-commerce comprehensive pilot zones significantly reduces annual sulfur dioxide (SO_2) emissions in cities after controlling for a series of variables and fixed effects. Mechanism analysis shows that the establishment of these pilot zones enhances green innovation levels, thereby reducing SO_2 emissions and improving environmental pollution by accelerating the development and utilization of clean energy, improving energy efficiency, and adopting clean production processes. Heterogeneity analysis reveals that the environmental pollution reduction effect of pilot zones is stronger in non-resource-based cities than in resource-based cities in terms of resource endowments, most significant in western regions geographically, and more pronounced in large cities than in small/medium-sized cities in terms of city size.

Based on the above conclusions, this paper proposes the following recommendations: Governments should increase policy support for resource-based cities to guide them out of the "resource curse," establish special funds to encourage enterprises to transform industries and develop low-pollution, high-value-added industries, such as characteristic tourism and cultural creativity industries combined with cross-border e-commerce, to reduce reliance on resource-intensive industries. Given the large space for industrial restructuring and the rapid development of cross-border e-commerce in western regions, they should be prioritized as key areas for pilot zone construction. It is necessary to increase investment in infrastructure to improve logistics efficiency, upgrade communication networks, and attract more e-commerce enterprises, while encouraging local enterprises to engage in green technological innovation through tax incentives, R&D subsidies, and other support to promote industrial structure optimization and environmental improvement. For small/medium-sized cities, infrastructure should be strengthened to improve logistics efficiency and ensure stable energy supply, special funds for cross-border e-commerce development should be established to support local enterprises in enhancing technological capabilities and innovation, and cooperation with universities and vocational colleges should be strengthened to offer specialized courses in e-commerce operations and green technology applications, cultivate professional talents, optimize resource allocation, and promote the green development of cross-border e-commerce. Nationwide, successful experiences and models of pilot zone construction should be summarized and promoted, support for green technological innovation should be enhanced to encourage enterprises to increase R&D investments, promote the widespread application of clean energy in cross-border e-commerce-related industries, and improve the environmental regulatory system to strengthen supervision of e-commerce enterprises, ensuring they strictly comply with environmental standards and achieve synergistic progress between trade growth and environmental protection.

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