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The impact of cross-border e-commerce on urban air quality: Evidence from China's pilot zones

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Abstract

Amid rapid urbanization and industrialization, the pressing challenge of air pollution, cross-border e-commerce (CBEC) has emerged as a potential driver of environmental governance in China. Using CBEC pilot zones as a quasi-natural experiment, this study employs a multi-period difference-in-differences model on panel data from 284 Chinese cities (2009–2022) to assess the effect of CBEC on urban air quality, measured by sulfur dioxide (SO_2) emissions. The findings revealed that CBEC significantly reduced SO_2 emissions, thereby improving air quality. Heterogeneity analysis indicated that this positive effect was more substantial in eastern regions, cities with better digital infrastructure, and those with relatively weaker environmental regulations. Mechanism analysis further identified three key pathways: green technology innovation, productive service industry agglomeration, and resource allocation optimization. The study suggests that deepening CBEC reforms and expanding pilot zones can serve as effective policy tools for synergistically advancing economic growth and environmental sustainability.

Keywords: Cross-border e-commerce; Cross-border e-commerce pilot zones; Urban air quality; Green technology innovation; Resource allocation; Productive service industry agglomeration

1. Introduction

In the era of "polycrisis" characterized by global climate change, ecological degradation, and deepening social inequality,[1] the traditional economic growth model at the expense of environmental and social well-being is no longer sustainable. Transitioning to sustainable development—that is, seeking synergistic progress between economic advancement and environmental health—has become a core agenda of the international community, prominently reflected in the United Nations' 2030 Sustainable Development Goals. This transition calls for moving beyond the neoclassical obsession with Gross Domestic Product (GDP) growth as a singular focus and returning to the holistic analytical framework advocated by classical political economy, which integrates historical perspective, interdisciplinary analysis, and concern for social structures.[2] Within this framework, any significant socio-economic phenomenon—including the digital transformation of global trade patterns—can be systematically assessed along the two interconnected yet sometimes conflicting dimensions of economic sustainability and environmental sustainability.[3]

Urbanization, as a major social transformation on par with industrialization and economic development, profoundly shapes human society and its living environment. Among various environmental factors, air quality stands out as one of the most immediately perceptible.[4] China's development trajectory offers a highly compelling real-world context for this theoretical examination. The "economic miracle" achieved since the reform and opening-up has been accompanied by severe environmental challenges, particularly air pollution, which has emerged as a critical bottleneck threatening public health, undermining residents' well-being, and constraining sustainable societal development.[5] According to the *2023 Report on the State of China's Ecological Environment*, among 339 prefecture-level and above cities, 136 exceeded air quality standards. In response, China has elevated pollution control to a national strategic priority, explicitly advocating for targeted, scientific, and systematic governance to synergistically reduce pollution and carbon emissions while continuously improving air quality. This fundamentally represents a profound correction of unsustainable production and development models. Within this macro-level transition, cross-border e-commerce (CBEC)—as a novel form of trade that restructures global trade organization and resource allocation through digital platforms[6]—urgently requires re-examination within the framework of sustainable development.

Cross-border e-commerce has profoundly impacted production, distribution, and consumption by reshaping the organizational methods of international trade and global resource allocation. From the production perspective, it accelerates enterprise digital transformation and refines management, compelling greater emphasis on green production and resource conservation.[6] Leveraging digital technologies, enterprises optimize production processes, improve energy efficiency, and reduce waste and pollutant emissions. Simultaneously, the rising global demand for eco-friendly products incentivizes enterprises to transition toward cleaner technologies and sustainable materials. In distribution, CBEC enhances logistics and supply chain management, improving transportation efficiency while minimizing resource wastage and unnecessary energy consumption.[7] On the consumption front, through information dissemination and platform mechanisms, it guides consumers toward green consumption preferences, thereby mitigating the overall environmental pressure of consumption activities.[8] In summary, by optimizing production methods, logistics models, and consumption patterns, CBEC demonstrates multi-dimensional green effects across the entire supply chain.

Consequently, we hypothesized an inherent logical connection between CBEC and urban air quality. If CBEC can indeed improve ecological environments and enhance urban air quality, what are the underlying mechanisms? Are there heterogeneous effects? Investigating the environmental effects of CBEC not only advances societal sustainable development but also offers valuable practical insights for formulating environmental governance policies.

Traditional research on trade and the environment has primarily focused on the Environmental Kuznets Curve (EKC) hypothesis or the "pollution haven/halo" hypothesis,[9,10] emphasizing the macro-level relationship between economic growth or traditional trade patterns and pollution. In recent years, studies have begun to explore the green potential of digital trade—defined as trade activities conducted or delivered via digital means.[11] These studies have found that digital trade can reduce carbon emissions and alleviate ecological pressure by enhancing resource allocation efficiency and information transparency.[12,13] However, such research has largely remained confined to the perspective of technological efficiency. As a prominent form of digital trade, CBEC also has considerable potential to advance green development.

However, existing studies exhibit a clear bias toward its economic sustainability dimensions, predominantly examining its contributions to reducing trade costs, expanding market access, fostering regional growth, and promoting industrial upgrading and innovation.[14-17] In contrast, research on the environmental sustainability effects of CBEC remains notably inadequate, both theoretically and empirically. The limited related literature either concentrates on the application of green technologies,[18] analyzes its effects on carbon emission efficiency at the enterprise level,[13] or preliminarily examines its inhibitory effect on sulfur dioxide (SO_2) emissions using panel data from Chinese cities between 2010 and 2018.[19] However, these studies still lack robustness tests, mechanism investigations, and systematic heterogeneity analyses. This fragmented research approach precisely reflects the widespread challenges of conceptual ambiguity and dimensional imbalance in current sustainability discourse.[20]

To systematically evaluate the effect of CBEC policies on the urban environment, this study selected the "CBEC pilot zones" as a quasi-natural experiment. Based on panel data from 284 Chinese cities from 2009 to 2022, we employed a multi-period difference-in-differences (DID) method to empirically examine the causal effects of these policies on urban air quality, and further explored their underlying mechanisms and heterogeneous effects. The selection of indicators is particularly critical in a research design. Existing studies commonly use various pollutants such as $PM_{2.5}$, PM_{10}, and CO_2 to measure air quality, but these indicators differ significantly in terms of pollution sources and policy sensitivity: $PM_{2.5}$ primarily reflects pollution from transportation and daily life, while CO_2 is mainly associated with long-term energy consumption and climate change. In contrast, industrial SO_2 emissions are highly concentrated in industrial production processes dominated by coal, and are directly linked to the energy structure, technological choices, and end-of-pipe management. As such, SO_2 serves as a typical indicator for characterizing industrial pollution intensity and local development models.[21] Particularly in the context of China's continued reliance on coal energy and heavy chemical industries, SO_2 is regarded as a representative outcome of the "growth at the expense of pollution" model. Its changes can sensitively reflect the actual effects of industrial restructuring, technological progress, and environmental regulations.[22] Therefore, this study focuses on industrial SO_2 emissions as a key environmental indicator for measuring urban air quality.

The marginal contributions of this study are as follows. First, from a theoretical perspective, we explicitly integrate the issue of CBEC into the analytical framework of sustainable development, aligning with the call to return to the holistic tradition of classical political economy.[2] This provides a more robust and nuanced conceptual foundation for understanding the relationship between digital trade and sustainable development. Second, in terms of empirical evidence, we not only reveal the positive effect of CBEC on urban air quality (measured by SO_2 emission reduction) but also preliminarily explore its mechanisms through three pathways—agglomeration effects, technological effects, and resource allocation effects—thereby enriching the theoretical framework of the environmental effects of CBEC. Third, regarding policy implications, our heterogeneity analysis shows that the realization of the environmental benefits of CBEC depends on supporting conditions, such as digital infrastructure and environmental regulations. This underscores the critical importance of adopting systematic, inclusive policies to maximize synergy between economic growth and environmental sustainability.

2. Policy background and research hypotheses

2.1. Policy background

As an innovative trade model combining the internet and international trade, CBEC has played an increasingly significant role in expanding foreign trade and related areas. In recent years, CBEC has achieved rapid growth. According to statistics from China Customs, the import and export values have increased from CNY 36 billion in 2015 to CNY 2.37 trillion in 2023, with an average annual growth rate of 19.38%. This progress has largely benefited from sustained policy support. Since 2012, the Chinese government has fostered a stable institutional environment for the standardized development of CBEC by improving institutional arrangements in payment and settlement, customs clearance and supervision, tax collection and management, and financial services. Additionally, CBEC has been consistently included in the Government Work Report for multiple years. Against this backdrop, CBEC pilot zones have been gradually established as a key vehicle for institutional innovation. The establishment of these pilot zones is not random but is based on cities' existing developmental foundations and policy feasibility. They are typically concentrated in regions with active CBEC activities, well-developed logistics and port infrastructure, and mature industrial and digital economies.

In the context of high-quality development and green transformation, the policy practice of CBEC pilot zones primarily operates through three mechanisms: First, leveraging the advantages of digital trade platforms and institutional innovation, these zones provide critical support for the research and development (R&D), application, and diffusion of green technologies by promoting enterprise digital transformation and enhancing innovation incentive mechanisms. Specifically, institutional arrangements in areas such as intellectual property protection, commercialization of technological achievements, and international market expansion of green products within the pilot zones enhance the anticipated returns and sustained motivation for enterprises to engage in green technological innovation, thereby fostering the continuous advancement of green innovation activities. Second, CBEC pilot zones significantly improve the environment for factor allocation through institutional innovation and platform-based operations. By implementing process reengineering and information sharing across customs clearance, settlement, and supervision, these zones reduce information asymmetry and transaction friction, facilitating the efficient flow of capital, technology, data, and other factors across broader scopes. Third, CBEC pilot zones markedly promote agglomeration and the

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development of related producer service industries by constructing a comprehensive industrial ecosystem. Centered around the core processes of CBEC, these zones accelerate the clustering of productive services such as logistics, finance, information services, technical support, and specialized intermediaries, forming an industrial network with platform enterprises at its core and multi-stakeholder collaborative development.

2.2. Research hypotheses

2.2.1. Effects of cross-border e-commerce on urban air quality

In facilitating the transformation and upgrading of foreign trade, CBEC prioritizes trade facilitation, as well as the environmental attributes of goods. Through enhanced international cooperation and alliances, CBEC enterprises collectively advance sustainable practices across the sector by sharing green technologies and management experiences, thereby mitigating negative environmental externalities.[14] Beyond fostering green supply chains, these enterprises assume broader social responsibilities. Their engagement in environmental initiatives and public welfare projects helps improve public perception and cultivates an eco-friendly brand image.[23] Such efforts effectively reduce pollution generated throughout production, logistics, and packaging processes, thereby contributing to better urban environmental outcomes. At the policy level, governments and industry associations have also introduced measures to accelerate CBEC's green transition. For instance, local authorities promote green packaging, warehousing, and low-carbon transportation to encourage sustainable industry development. The revised national standard for *Express Packaging Materials* strengthens environmental requirements by emphasizing reduction, greening, and recyclability, helping curb over-packaging and promoting greener logistics. Alongside the express industry's shift toward sustainability, the adoption of eco-friendly delivery vehicles—such as electric vehicles and bicycles—has reduced exhaust emissions, leading to measurable improvements in urban air quality. Furthermore, the establishment of CBEC pilot zones is viewed as a key policy instrument for promoting green development in the sector. Focusing specifically on urban environmental performance, Ma and Zhang[19] provided preliminary evidence that CBEC significantly curbs SO_2 emissions, with stronger effects observed in economically developed cities and those with a larger secondary industry base. This suggests that CBEC serves not only as an engine of economic growth but also as a positive force in ecological transition and urban environmental governance. Based on the above analysis, the following hypothesis was proposed: H_1: CBEC can reduce SO_2 emissions, thereby improving urban air quality.

2.2.2. Cross-border e-commerce, green technology innovation, and urban air quality

Under the longstanding GDP-oriented paradigm of regional competition, a "race to the bottom" approach has prevailed across most regions of China, where environmental quality was often traded off for short-term economic expansion. This distortion in the allocation of environmental and productive factors weakened enterprise incentives to reduce emissions, resulting in persistent issues such as high-sulfur fuel consumption and inadequate investment in end-of-pipe treatment, thereby sustaining industrial SO_2 emissions at elevated levels.[24] The establishment of CBEC pilot zones mitigates administrative distortions, reinforces market competition mechanisms, and institutionalizes the conditions for factor mobility and fair competition, enabling the market to play a more decisive role in resource allocation.[6] Within this institutional environment, enterprises simultaneously face intensified competitive and environmental constraints. On one hand, heightened marketization pressures enterprises to lower pollution per unit of output through technological upgrading. On the other hand, the improved policy landscape channels capital, technology, and talent toward enterprises capable of green innovation, laying the essential foundation for technological advancement in sustainability. To support CBEC pilot zones, local governments typically implement policy packages including tax incentives and innovation subsidies. These measures create a "policy lowland effect," attracting an agglomeration of capital, labor, and technology,[25] which not only supplies vital resources for green R&D but also escalates market competition—compelling enterprises to pursue green innovation for cost and market advantages.[26] Meanwhile, the rapid growth of CBEC digitizes information, logistics, and capital flows, substantially lowering transaction and management costs. The freed resources can be redirected toward upgrading production processes and adopting desulfurization equipment.[16]

From an emission mechanism perspective, green technological innovation curtails industrial SO_2 emissions through three direct pathways: (i) enhancing production efficiency and energy utilization to reduce dependence on high-sulfur fuels, thereby limiting SO_2 generation at the source; (ii) promoting substitution with clean energy and low-sulfur alternatives, thus restructuring energy consumption and lowering sulfur emissions from industrial combustion; and (iii) applying advanced desulfurization and end-of-pipe technologies to improve pollution treatment efficiency and cut actual emissions.[27,28] Collectively, these mechanisms enable green innovation to effectively suppress SO_2 emission intensity and enhance overall environmental performance. Based on the above analysis, the following hypothesis was proposed: H_2: CBEC reduces SO_2 emission by promoting green technological innovation, thereby improving urban air quality.

2.2.3. Cross-border e-commerce, resource allocation, and urban air quality

Industrial SO_2 emissions largely result from inefficient resource allocation, which perpetuates extensive and pollution-intensive modes of production. When capital, energy, and labor remain concentrated in high-consumption, high-emission sectors over the long term, pollution per unit of output rises, while incentives for enterprises to adopt cleaner technologies and improve energy efficiency are weakened.[29] Hence, enhancing resource allocation efficiency and reducing factor misallocation form a crucial institutional basis for lowering SO_2 emissions. As a digitally enabled model of foreign trade, CBEC breaks down regional and national barriers, facilitates the cross-border flow of production factors, and improves overall resource allocation efficiency. First, CBEC fosters integration within global e-commerce supply chains, allowing capital, technology, and intermediate goods to be allocated more efficiently across borders.[30] This reallocation of resources across sectors and regions reduces the operational space for polluting and low-efficiency enterprises, thereby lowering aggregate industrial emission intensity. Second, supported by digital technologies, CBEC platforms utilize big data and cloud computing to achieve precise matching of supply and demand. This reduces overstocking, minimizes redundant production, and increases resource utilization. By curbing inefficient consumption of energy and raw materials, this matching mechanism helps lower sulfur emissions from industrial activities. Furthermore, leveraging the "experimental" policy advantages of CBEC pilot zones, automation and intelligent technologies replace inefficient, pollution-intensive labor in production, optimizing the composition of factor inputs.[31] Simultaneously, growing demand for knowledge- and technology-intensive roles in the digital economy directs resources toward higher-value, lower-emission industries, supporting the structural transition toward greener industrial development.

In terms of emission outcomes, improved resource allocation efficiency directly reduces industrial SO_2 emissions by phasing out inefficient capacity, scaling down pollution-intensive production, and raising energy productivity. It also strengthens enterprises' ability to adopt energy-saving equipment and pollution control technologies, creating a sustainable foundation for emission reduction.[32] Based on the above analysis, the following hypothesis was proposed: H_3: CBEC reduces SO_2 emissions by enhancing resource allocation optimization, thereby improving urban air quality.

2.2.4. Cross-border e-commerce, productive service industry agglomeration, and urban air quality

The agglomeration of the productive service industry has been proven to be an effective pathway for reducing environmental pollution and improving environmental quality.[33] Functioning as critical supporting sectors for manufacturing, productive services—encompassing R&D, design, information services, modern logistics, and financial intermediation—embed themselves deeply within manufacturing production processes. This integration substantially shapes enterprises' technological choices, production organization, and energy consumption structures. From an emissions-reduction perspective, productive service-industry agglomeration influences SO_2 emissions through three principal channels. First, the concentration of R&D, design, and technical services enhances manufacturers' access to cleaner production technologies and energy-saving solutions, encouraging the adoption of low-sulfur raw materials and clean combustion technologies. Second, the development of modern logistics and supply chain services reduces energy waste in transportation and warehousing, indirectly lowering the overall sulfur emissions. Third, the clustering of financial and information services alleviates financing constraints for enterprises' green transformation and enhances their capacity to invest in desulfurization equipment and environmental technologies.[34] Concurrently, productive service industry agglomeration enhances specialization and economies of scale, raising total factor productivity while reducing energy use and emissions per unit of output.[35] This efficiency gain helps phase out energy- and emission-intensive production stages, contributing to a systemic decline in SO_2 emissions.[36]

In practice, the development of CBEC pilot zones has significantly accelerated the clustering of producer services—such as logistics, customs clearance, information technology, and legal support—by attracting leading enterprises and strengthening industrial ecosystems.[37] Leveraging institutional innovation and trade facilitation, these zones foster an integrated industrial ecology centered on CBEC, deepening synergies between manufacturing and productive services.[25] These synergies not only improve industrial chain efficiency but also promote a structural shift toward less polluting and lower-emission production through better resource allocation and technology diffusion. Based on the above analysis, the following hypothesis was proposed: H_4: CBEC reduces SO_2 emissions by productive service industry agglomeration, thereby improving urban air quality.

3. Methodology

3.1. Model development

To address institutional barriers and structural challenges to CBEC development, the Chinese government initiated the establishment of CBEC pilot zones in 2015. By November 2022, 165 CBEC pilot zones had been established across 31 provinces. Given the continuity of sample data, we selected the cities from the first five batches of CBEC pilot zones as the sample. Treating the establishment of CBEC pilot zones as a quasi-natural experiment and building on the theoretical framework outlined earlier, this paper employed a DID method to assess their effects on urban air quality. The specific model setup is as follows (**Equation 1**):

$$Uaq_{it} = \alpha_0 + \alpha_1 Policy_{it} + \alpha_2 Controls_{it} + \delta_i + \mu_t + \varepsilon_{it} \quad (1)$$

where i and t denote cities and years, respectively, Uaq represents urban air quality, α_0 is the intercept term, $Policy_{it}$ is the explanatory variable, $Controls_{it}$ denotes a vector of city-level control variables, δ_i and μ_t denote city and year fixed effects, respectively, and ε_{it} represents the idiosyncratic error term.

3.2. Variable settings

Urban air quality (Uaq) was the dependent variable. In line with the data availability of urban air pollution indicators and following the approach of Guo *et al.*,[29] this study employed two measures: total SO_2 emissions ($lnso_2$) and per capita SO_2 emissions ($lnpso_2$) to quantify urban air quality.

The explanatory variable ($Policy$) captures the establishment of CBEC pilot zones. It was constructed as the interaction term $Treat_i \times Post_t$, where $Treat_i$ is a dummy variable indicating whether the city i belongs to a pilot zone, and $Post_t$ is a time dummy that equals 1 in and after the year when the pilot policy was implemented. The coefficient on this interaction term reflects the causal effect of the CBEC pilot zone policy.

The mechanism variables included:

(i) Green technology innovation ($Greentec$). The variable $Greentec$ was constructed using patent data sourced from China's National Intellectual Property Administration, with green patents further identified based on the *International Patent Classification Green Inventory* published by the World Intellectual Property Organization in 2010. In line with Zhang *et al.*[38] and Bilal *et al.*,[39] patents meeting the green innovation definition and classification criteria were selected, and the number of green patent applications per 10,000 people in each city was calculated to measure urban green technology innovation. Green patent counts serve as the core proxy for this variable.

(ii) Resource allocation (Ra). Ra was measured using total factor productivity at the city level, calculated via the Malmquist index. Widely employed in productivity analysis, especially for multi-period efficiency comparisons,[40] the Malmquist index captures changes in total factor productivity over time, thereby reflecting shifts in resource allocation efficiency. The index is defined as follows (**Equation 2**):

$$M_{t,t+1} = \frac{Y_{t+1}}{Y_t} \times \frac{X_{t+1}}{X_t} \quad (2)$$

where $M_{t,t+1}$ denotes the Malmquist index between periods t and $t+1$; Y_t and Y_{t+1} represent real GDP in each period; and X_t and X_{t+1} denote total inputs, including capital stock and labor employment.

(iii) Productive service industry agglomeration ($Psia$). Following the approach of Guo and Huang[41], this study measured $Psia$ using the location quotient (LQ) index. The LQ is calculated as follows (**Equation 3**):

$$Psia_{it} = \frac{B_{it} / E_{it}}{\sum_{i=1}^{n} B_{it} / \sum_{i=1}^{n} E_{it}} \quad (3)$$

where B_{it} represents employment in productive services in the city i in year t, and E_{it} denotes total employment in the city i in year t. The LQ reflects the relative concentration of the productive services within a city's employment structure. A higher LQ value indicates a stronger degree of agglomeration in productive services.

The control variables included:

(i) Economic development ($pgdp$): Measured as the natural logarithm of regional GDP per capita. Following the EKC hypothesis, which posits an inverted U-shaped relationship between economic growth and pollution, we also included $pgdp^2$ to capture potential nonlinear effects. Economic expansion in the early stages may increase pollution, but beyond a certain threshold, technological advancement and environmental policy implementation could reduce emissions.

(ii) Financial development ($finance$): Represented by the natural logarithm of the total deposit and loan balance of financial institutions. Financial sector growth facilitates capital mobility and technological innovation, which in turn can shape environmental governance and emission levels. A well-developed financial system may indirectly support improvements in urban air quality by funding green investments and cleaner technologies.

(iii) Industrial structure ($indus$): Defined as the share of secondary industry valueadded in GDP. Industrial composition—especially the weight of heavy manufacturing—is strongly correlated with pollution. Cities with a larger secondary sector typically experience higher emissions, underscoring the need to account for structural effects on air quality.

(iv) Government intervention (gov): Measured as the ratio of local government fiscal expenditure to GDP. Public spending influences environmental outcomes through regulatory enforcement, infrastructure investment, and pollution control initiatives. Higher fiscal outlays often signal stronger environmental governance and may contribute to improved air quality.

(v) Population density (pop): Represented by the natural logarithm of population per square kilometer. Density affects transportation demand, energy use, and agglomeration-related emissions. Denser populations tend to generate greater pollution, necessitating control for this demographic factor.

(vi) Urban technological innovation ($tech$): Captured by the natural logarithm of invention patents per 10,000 people. Innovation is a key driver of green transition and pollution abatement. Technologically advanced cities may adopt cleaner production methods and reduce industrial emissions; therefore, including this variable helps isolate the specific effect of CBEC on air quality.

This study employed panel data covering 284 Chinese cities from 2009 to 2022. Data were drawn from the *China Urban Statistical Yearbook*, *China Environmental Statistical Yearbook*, selected municipal annual reports, and the EPS database. Descriptive statistics of all variables are presented in Table 1.

4. Results and discussion

4.1. Baseline regression

Table 2 presents the baseline estimation of the effect of establishing CBEC pilot zones on urban air quality. In Columns (1) and (3), which control only for city and year fixed effects, the coefficient on the policy variable was significantly negative for both $lnso_2$ and $lnpso_2$. This indicates that the establishment of CBEC pilot zones was associated with a clear reduction in air pollution. After further incorporating all control variables in Columns (2) and (4), the policy effect remained significantly negative. These results confirm that establishing CBEC pilot zones led to a statistically significant improvement in urban air quality, providing empirical support for H_1.

Table 1. Descriptive statistics

Variables	Observations	Mean	Standard deviation	Mininum	Maximum
$lnso_2$	3,962	9.739	1.368	1.099	13.281
$lnpso_2$	3,962	3.900	1.338	0.034	7.796
Policy	3,962	0.102	0.302	0	1.000
pgdp	3,962	10.688	0.630	4.595	13.056
$pgdp^2$	3,962	114.632	13.396	21.115	170.451
finance	3,962	2.512	1.272	0.588	21.301
indus	3,962	0.457	0.111	0.107	0.897
gov	3,962	0.200	0.116	0.044	2.223
pop	3,962	5.897	0.680	3.433	8.137
tech	3,962	0.017	0.017	0.001	0.207

Table 2. Baseline regression results of the effect of cross-border e-commerce pilot zones on urban air quality

Variables	$lnso_2$		$lnpso_2$	
	(1)	(2)	(3)	(4)
Policy	−0.171** (−2.57)	−0.154** (−2.39)	−0.210*** (−3.41)	−0.183*** (−2.88)
pgdp	-	0.833 (0.86)	-	0.912 (0.85)
$pgdp^2$	-	−0.040 (−0.88)	-	−0.038 (−0.76)
finance	-	−0.004 (−0.17)	-	0.002 (0.08)
indus	-	0.799* (1.77)	-	0.479 (1.17)
gov	-	−0.268 (−0.79)	-	−0.143 (−0.40)
pop	-	−0.162 (−0.64)	-	−0.217 (−1.13)
tech	-	−1.519 (−0.88)	-	−2.632 (−1.61)
Constant	9.756*** (1,434.34)	6.118 (1.13)	3.921*** (624.22)	−1.578 (−0.27)
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Obs	3,962	3,962	3,962	3,962
R^2	0.875	0.885	0.890	0.900

Notes: ** and *** indicate significance at the 5% and 1% significance levels, respectively. The standard errors indicated in parentheses are clustered at the city level.
Abbreviations: FE: Fixed Effects; Obs: Observations.

4.2. Parallel trend and dynamic effect tests

A key identifying assumption of the DID method is that, prior to the establishment of CBEC pilot zones, air pollution levels in treatment and control cities followed parallel trends. Following the event-study framework proposed by Wang *et al.*,[30] we estimated the following model using **Equation 4**:

$$Uaq_{it} = \alpha_0 + \sum_{k=-5,k\neq-1}^{4} \alpha_k Policy_{i,t_0+k} + \eta Controls_{it} + \delta_i + \mu_t + \varepsilon_{it} \quad (4)$$

where t_0 denotes the year in which a CBEC pilot zone is established in city i, and $Policy_{i,t_0+k}$ is a dummy variable equal to 1 if city i is observed k years relative to the policy implementation year, and 0 otherwise. The reference period was set to the year before the policy took effect ($k=-1$), which was omitted from the regression. Given that the first batch of pilot zones was established in 2015 and the sample ended in 2022, the maximum possible k was 7. Due to limited pre- and post-policy observations, we grouped the five years before the policy into period $k=-5$ and the four years after into period $k=4$. The estimated coefficients α_k are shown in Figure 1. The results showed that all pre-policy coefficients were statistically insignificant, supporting the parallel-trend assumption. In the post-policy periods, most coefficients were significantly negative, consistent with the baseline regression. This pattern confirms the suitability of the DID design for evaluating the effect of CBEC pilot zones on urban air quality and further substantiates the core finding of this study: the CBEC pilot zone policy exerts a lasting and significant effect on air quality.

4.3. Robustness test

4.3.1. Placebo test

To address concerns that unobserved factors or omitted variables may bias our estimates, we conducted a placebo test following Li *et al.*[13] The test constructed a fictitious policy shock by randomly assigning cities—equal in number to the actual CBEC pilot zones—to a pseudo-treatment group. A simulated policy dummy was then incorporated into the baseline regression model. If the baseline results were robust and not driven by omitted variables or other random factors, the coefficient on this placebo policy variable should be statistically indistinguishable from zero. We repeated this randomization process 500 times and plotted the distribution of the estimated coefficients (Figure 2). The results showed that the placebo coefficients were tightly centered around zero and followed an approximately normal distribution. In contrast, the estimated coefficient

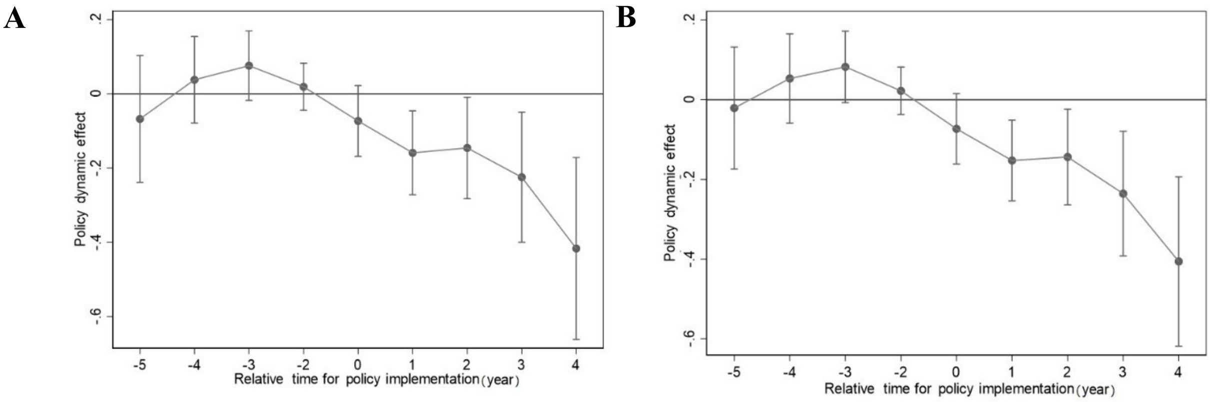

Figure 1. Parallel trend and dynamic effect tests of (A) *lnso*$_2$ and (B) *lnpso*$_2$.

from the actual policy variable lay clearly outside this simulated distribution. This confirms that the observed improvement in urban air quality associated with CBEC pilot zones is unlikely to be attributable to omitted variables or random factors, supporting the robustness of our main findings.

4.3.2. Instrumental variable estimation

To address potential endogeneity arising from reverse causality or omitted variables in the relationship between CBEC pilot zones and urban air quality, we employed an instrumental variable (IV) approach. Following the strategy of Nunn and Qian,[42] we constructed two instruments: (i) IV1: the interaction between the lagged national number of internet users and the number of post offices per 100 people in 1984; and (ii) IV2: the interaction between the number of post offices per 100 people in 1984 and the number of telephones per 100 people in 1984.

We estimated a two-stage least squares model, with results reported in Table 3. Columns (1) and (2) present the first-stage estimates, which showed that both instruments were positively and significantly correlated with the CBEC policy, regardless of whether control variables were included. Tests for weak instruments confirm the relevance of the selected IVs. The second-stage results are shown in Columns (3)–(6). Columns (3) and (4) correspond to $lnso_2$, while Columns (5) and (6) correspond to $lnpso_2$. In all specifications, the coefficient on the policy variable remained significantly negative, indicating that the establishment of CBEC pilot zones significantly reduces both total and per capita SO_2 emissions. These findings are consistent with the baseline regression results and reinforce the reliability of our core conclusion.

4.3.3. Propensity score matching–difference-in-differences test

To further account for systematic differences between cities with and without CBEC pilot zones that may affect air

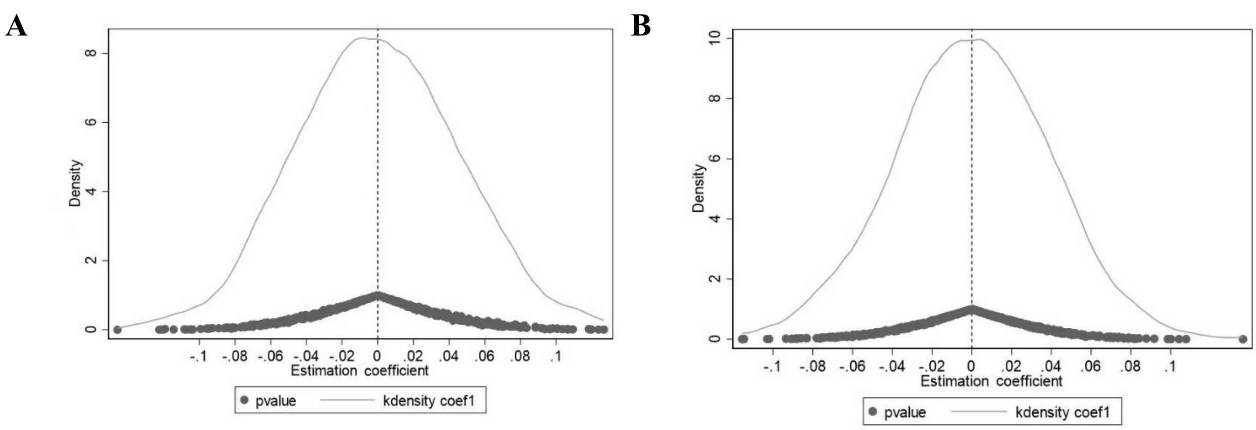

Figure 2. Distribution of estimated coefficients for placebo policy dummy variables of (A) *lnso*$_2$ and (B) *lnpso*$_2$.

Table 3. Two-stage least squares model estimation results

Variables	*Policy*		*lnso₂*		*lnpso₂*	
	(1)	(2)	(3)	(4)	(5)	(6)
IV1	0.253*** (10.41)	0.191*** (13.66)	-	-	-	-
IV2	0.251*** (9.81)	0.180*** (6.48)	-	-	-	-
Policy	-	-	−1.125*** (−3.52)	−1.446*** (−7.84)	−0.903*** (−4.10)	−0.890*** (−2.36)
Controls	No	Yes	No	Yes	No	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Kleibergen-Paap LM	44.760 ***	190.379 ***	-	-	-	-
Kleibergen-Paap Wald F	108.318 [16.38]	186.614 [16.38]	-	-	-	-
R^2	-	-	0.287	0.466	0.194	0.177
Obs	2,902	2,902	2,902	2,902	2,902	2,902

Notes: Standard errors clustered at the city level are reported in parentheses. *** denotes statistical significance at the 1% level. [] Square brackets are a conventional expression in the Kleibergen-Paap Wald F test.
Abbreviations: FE: Fixed Effects; LM: Lagrange multiplier; Obs: Observations.

quality, we employed the propensity score matching–DID test. First, we estimated the propensity score using a logit model, with the dependent variable indicating whether a city established a CBEC pilot zone. The matching covariates included economic development ($pgdp$ / $pgdp^2$), financial development ($finance$), industrial structure ($indus$), government intervention (gov), population density (pop), and technological innovation ($tech$). Second, based on the estimated scores, we implemented 1:1 k-nearest-neighbor matching to construct a control group that closely matches the treatment group on observable characteristics. A balance check confirmed that there were no significant differences in the baseline covariates between the matched groups. Finally, we re-estimated the DID model using the matched sample. As shown in Table 4, the coefficients on the policy interaction term remained significantly negative, consistent with the baseline results obtained from the full sample. This confirms that sample selection bias does not drive our main findings, further supporting the robustness of the conclusion that CBEC pilot zones contribute to the improvement of urban air quality.

4.3.4. Exclusion of confounding policies

To address potential confounding due to overlapping policy shocks, this study controlled for concurrent initiatives that may similarly influence urban development and environmental outcomes, such as innovation city pilot programs and broadband city initiatives.[43] Dummy variables representing these policies were incorporated into the baseline regression model. The results, reported in Table 5, showed that the coefficient on the CBEC policy remained significantly negative across all regression models—whether other policies were added individually (Columns [1]–[3] and [5]–[7]) or collectively (Columns [4] and [8]). Moreover, the magnitude of the estimated effect did not materially differ from the benchmark results. This suggests that the observed improvement in urban air quality following the establishment of CBEC pilot zones is not driven by concurrent policy interventions, thereby reinforcing the validity and robustness of our earlier findings.

4.3.5. Exclusion of COVID-19 pandemic effects (2020–2022)

To examine whether the exceptional fluctuations in economic activity and pollution emissions during the COVID-19 pandemic (2020–2022) affected the robustness of our core findings, we restricted the sample to the pre-pandemic period (i.e., ending in 2019) and re-estimated the baseline model. Results reported in Table 6 showed that

Table 4. Propensity score matching–difference-in-differences test results

Variables	$lnso_2$	$lnpso_2$
Policy	−0.150** (−2.36)	−0.130** (−2.22)
Controls	Yes	Yes
City FE	Yes	Yes
Year FE	Yes	Yes
R^2	0.876	0.903
Obs	3,960	3,960

Notes: Standard errors clustered at the city level are reported in parentheses. ** denotes statistical significance at the 5% level.
Abbreviations: FE: Fixed Effects; Obs: Observations.

Table 5. Results of excluding confounding policies

Variables	$lnso_2$				$lnpso_2$			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Policy	−0.154** (−2.40)	−0.168*** (−2.64)	−0.144** (−2.28)	−0.155** (−2.49)	−0.134** (−2.28)	−0.147** (−2.51)	−0.126** (−2.17)	−0.135** (−2.37)
Constant	6.096 (1.11)	5.738 (1.01)	6.329 (1.21)	5.947 (1.07)	5.145 (0.89)	4.799 (0.80)	5.304 (0.94)	5.101 (0.85)
innocity	Yes	-	-	Yes	Yes	-	-	Yes
lowcartoncity	-	Yes	-	Yes	-	Yes	-	Yes
broadbandcity	-	-	Yes	Yes	-	-	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.876	0.876	0.876	0.876	0.893	0.894	0.894	0.894
Obs	3,962	3,948	3,948	3,948	3,962	3,948	3,948	3,948

Notes: Standard errors clustered at the city level are reported in parentheses. ** and *** indicate significance at the 5% and 1% significance levels, respectively.
Abbreviations: FE: Fixed Effects; Obs: Observations. *Innocity* = innovation city; *lowcartoncity* = low-carbon city construction; *broadbandcity* = broadband city.

after removing pandemic-year data, the sign, significance, and economic magnitude of the main explanatory variable remained highly consistent with the benchmark estimates. This confirms that the long-term relationship and underlying mechanism identified in this study were not systematically distorted by the short-term disruptions caused by the pandemic, further supporting the robustness of our conclusions.

4.3.6. Other robustness tests

(a) Changing the dependent variable

Following the approach of Guo and Shi,[44] this study replaced the original dependent variable with $PM_{2.5}$ concentration as an alternative measure of urban air pollution. $PM_{2.5}$, which originates from industrial processes and residential activities, is widely regarded as a primary contributor to haze pollution. We therefore conducted robustness tests by substituting this indicator into the baseline regression. Notably, due to data availability—the latest $PM_{2.5}$ data used here extended only to 2020 (source: Center for International Earth Science Information Network, Columbia University)—the sample size for this regression

Table 6. Results after excluding the effect of the COVID-19 pandemic (2020–2022)

Variables	$lnso_2$	$lnpso_2$
Policy	−0.362** (−4.36)	−0.372** (−4.84)
Controls	Yes	Yes
City FE	Yes	Yes
Year FE	Yes	Yes
R^2	0.875	0.879
Obs	3,121	3,121

Notes: Standard errors clustered at the city level are reported in parentheses. ** denotes statistical significance at the 5% level.
Abbreviations: FE: Fixed Effects; Obs: Observations.

was reduced. The results, presented in Columns (1) and (2) of Table 7, showed that the coefficient on the CBEC pilot zone policy remained significantly negative regardless of whether control variables were included. This consistency further supports the robustness of the baseline findings.

(b) Reanalyzing the difference variables

In the baseline regression, the policy dummy variable was set to 1 in the year of implementation and all subsequent years. Since the policy announcement dates often fell mid-year—suggesting that full implementation may not have been achieved within the same calendar year—we refined the post-policy indicator following the approach of Lu *et al.*[45] Specifically, we assigned a fractional value to the implementation year reflecting the proportion of the year after the announcement, and set the indicator to 1 for all following years. The adjustments are as follows:

- First batch (March 2015): Post = 5/6 for 2015, then 1.
- Second batch (January 2016): Post = 1 for 2016 onward.
- Third batch (July 2018): Post = 1/2 for 2018, then 1.
- Fourth batch (December 2019): Post = 1/12 for 2019, then 1.
- Fifth batch (April 2020): Post = 7/12 for 2020, then 1.

Moreover, because the sixth and seventh batches were established in 2022 and their policy effects had not yet fully released by the end of our sample period, these cities were reclassified into the control group for this robustness check. The regression results based on this adjusted timing variable are reported in Columns (3) and (4) of Table 7. The coefficient on the policy variable remained significantly negative, with a magnitude comparable to the baseline estimates. This confirms that our main findings are robust to alternative definitions of policy timing.

(c) Considering policy anticipation effects

To examine whether potential anticipation effects prior to the establishment of CBEC pilot zones might confound our estimates, we modified **Equation 1** by including an interaction term between the policy dummy and a dummy variable, indicating the year before the policy was implemented. The results, presented in Columns (5) and (6) of Table 7, showed that this interaction term was statistically insignificant. This suggests that there were no notable anticipatory changes in air quality in the year preceding the policy introduction, supporting the assumption that the establishment of CBEC pilot zones can be treated as an exogenous policy shock.

(d) Considering lagged policy effects

To account for the possibility that the effect of CBEC pilot zones on air quality may unfold with a time lag, we lagged both the core policy variable (*Policy*) and all control variables by one period, thereby mitigating potential simultaneity bias. Results reported in Columns (7) and (8) of Table 7 showed that the coefficient on the lagged policy interaction remained significantly negative. This finding is consistent with earlier results and reinforces the conclusion that establishing CBEC pilot zones contributes to improved air quality, with observable effects that persist over time.

(e) Excluding central cities

Given potential differences in administrative authority and resource allocation between central cities (e.g., provincial capitals, sub-provincial cities, and municipalities) and ordinary prefecture-level cities, we removed central cities from the sample. The results confirm that the policy still significantly reduces air pollution: coefficients for $lnso_2$ and $lnpso_2$ were −0.103 and −0.092 ($p < 0.1$), respectively.

This supports the robustness of our findings.

4.4. Heterogeneity tests

4.4.1. Geographic location heterogeneity

To further explore the geographic heterogeneity in the effect of establishing CBEC pilot zones on urban air quality, this study categorized the sample cities into eastern and central-western regions according to the classification of China's National Bureau of Statistics. The eastern group comprised 11 provinces (including municipalities and autonomous regions), including Beijing, Shanghai, and Zhejiang, while the central-western group included 20 provinces, exemplified by Shanxi and Jilin. As presented in Columns (1)–(4) of Table 8, the policy effects exhibited significant geographic variation. The policy coefficient was significantly negative for cities in the eastern region, whereas it was statistically insignificant for those in the central-western region. This suggests that the ecological and environmental benefits of the CBEC pilot zone policy are more pronounced in eastern cities.

The observed heterogeneity can be explained by the following factors. First, eastern cities have higher GDP and more concentrated economic activity than their central-western counterparts, resulting in greater energy consumption and pollution emissions. The establishment of CBEC pilot zones in these areas has not only stimulated growth in logistics, transportation, and warehousing but also accelerated the adoption of green technologies and enhanced pollution control measures. Second, the greater economic and industrial agglomeration in eastern cities exposes them to a higher density of pollution sources, such as construction dust and emissions from the catering sector. The CBEC pilot zone policies contribute to significant improvements in environmental quality in these contexts by fostering green technology innovation and elevating environmental awareness. Furthermore, existing literature highlights the critical role of policy enforcement in environmental governance.[46] Governments in eastern regions generally benefit from more abundant fiscal resources and stronger governance capacities, which enable more rigorous policy implementation and greater effectiveness in executing various policies, including those pertaining to environmental protection and sustainable development.[47] In contrast, governments in central-western cities often face constraints in fiscal and administrative capabilities, leading to comparatively weaker policy enforcement and insufficient investment in green initiatives.[48] These limitations potentially hinder the full realization of the environmental benefits associated with the CBEC pilot zone policy in these regions.

4.4.2. Digital infrastructure heterogeneity

Digital infrastructure extends beyond traditional hardware

Table 7. Results of other robustness tests

Variables	Dependent variable replaced		Reanalyzing differential variables		Policy expected effects		Policy lag effects	
	$PM_{2.5}$	$PM_{2.5}$	$lnso_2$	$lnpso_2$	$lnso_2$	$lnpso_2$	$lnso_2$	$lnpso_2$
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Policy	−0.024** (−2.59)	−0.017** (−2.09)	−0.140** (−2.31)	−0.123** (−2.19)	−0.137** (−2.07)	−0.122** (−2.00)	−0.187*** (−2.99)	−0.169*** (−2.94)
Pilot cities × One year prior to policy	-	-	-	-	0.019 (0.34)	0.001 (0.04)	-	-
Controls	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.951	0.952	0.876	0.893	0.876	0.893	0.889	0.897
Obs	3,405	3,405	3,962	3,962	3,962	3,962	3,678	3,678

Notes: Standard errors clustered at the city level are reported in parentheses. ** and *** indicate significance at the 5% and 1% significance levels, respectively.
Abbreviations: FE: Fixed Effects; Obs: Observations.

Table 8. Heterogeneity test results

Variables	Geographical location				Digital infrastructure				Environmental regulations			
	Eastern cities		Midwest cities		High		Low		High		Low	
	lnso₂	*lnpso₂*	*lnso₂*	*lnpso₂*	*lnso₂*	*lnpso₂*	*lnso₂*	*lnpso₂*	*lnso₂*	*lnpso₂*	*lnso₂*	*lnpso₂*
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Policy	−0.213** (−2.48)	−0.185** (−2.34)	−0.005 (−0.06)	−0.001 (−0.02)	−0.130** (−2.14)	−0.093* (−1.68)	−0.216 (−0.81)	−0.175 (−0.69)	−0.114* (−1.66)	−0.095 (−1.54)	−0.188** (−2.02)	−0.174** (−2.08)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.904	0.913	0.865	0.888	0.903	0.922	0.856	0.881	0.897	0.904	0.881	0.897
Obs	1,357	1,357	2,605	2,605	2,114	2,114	1,834	1,834	1,918	1,918	1,899	1,899

Notes: Standard errors clustered at the city level are reported in parentheses. * and ** indicate significance at the 10% and 5% significance levels, respectively.
Abbreviations: FE: Fixed Effects; Obs: Observations.

networks to encompass a complex, interconnected system of technological frameworks, protocols, data, services, and governance mechanisms that underpin the functioning of a digital society and economy.[49] Well-developed digital infrastructure can provide CBEC enterprises with higher-quality internet services. To investigate this dimension of heterogeneity, this study employed the urban internet penetration rate as a proxy for digital infrastructure, defined as the proportion of urban broadband subscribers relative to the city's total resident population at year-end. Data were drawn from various city statistical yearbooks and the *China Urban Statistical Yearbook*. Using the initial sample year (2011), we calculated the internet penetration rate for each city. Descriptive statistics for this indicator (mean: 15.2%, standard deviation: 7.8%, median: 14.1%) guided our grouping approach: cities were divided into higher- and lower-level digital infrastructure groups based on the median value of 14.1%. This median-based split is a commonly used, methodologically robust procedure that ensures roughly balanced group sizes and facilitates comparative analysis. The regression results for these subgroups are presented in Columns (5) to (8) of Table 8. In cities with higher levels of digital infrastructure, the coefficient for establishing CBEC pilot zones was significantly negative, whereas in cities with lower levels, the policy coefficient was statistically insignificant. This suggests that the ecological and environmental benefits of the policy are contingent upon a certain threshold of digital infrastructure development.

The observed pattern can be explained as follows. In regions with more advanced digital infrastructure, enterprises encounter lower barriers and achieve higher efficiency in accessing the internet, utilizing e-commerce platforms, and adopting digital technologies. When CBEC pilot zone policies are introduced, enterprises in these regions can respond more swiftly and comprehensively to policy incentives, engaging in digitized and networked cross-border trade activities. Prior research indicates that robust digital infrastructure significantly reduces enterprises' information acquisition and transaction costs,[50] thereby enhancing their responsiveness to emerging market opportunities and policy incentives.[51] This not only accelerates industrial upgrading and business model innovation but also lays the technical groundwork for integrating and deploying digital emission-reduction solutions—such as green logistics technologies and intelligent warehouse management systems. Indeed, the convergence of digital technology and green innovation has been identified as a key pathway to advancing low emissions.[52] Thus, digital infrastructure amplifies the green transformation potential of CBEC pilot zone policies by improving policy dissemination efficiency and strengthening technological integration capabilities.

4.4.3. Environmental regulation intensity heterogeneity

Environmental regulation intensity refers to the degree and stringency of government-imposed constraints and influences on the environmental behavior of economic agents through laws, regulatory policies, and administrative measures.[53] Such regulations aim to protect the environment and can directly improve regional environmental quality, while also influencing the conduct of enterprises in the CBEC sector and, consequently, their environmental effect. Instruments such as environmental taxes and statutory requirements may raise operational costs for e-commerce businesses, prompting them to adopt greener technologies and ultimately contributing to improved environmental outcomes.

Following the approach of Chen and Chen,[54] this study used the frequency and proportion of environment-related terms in municipal government work reports as a proxy for environmental regulation intensity. These terms include, but are not limited to, "environmental protection," "pollution control," "energy conservation and emission reduction," "carbon emissions," and "SO_2 emissions." The environmental regulation intensity is calculated using **Equation 5**:

$$\text{ERI}=\frac{\sum_{i=1}^{n}\text{Frequency of environmentally related terms}_i}{\text{Total number of words in the reports}}\times 100\,\% \quad (5)$$

where the numerator represents the total number of occurrences of all environment-related terms in government work reports.

The descriptive statistics of this variable were: mean = 1.65%, standard deviation = 0.92%, median = 1.51%. Using the median value (1.51%) as the threshold, we divided the sample into high- and low-intensity environmental regulation groups. The test results are shown in Columns (9)–(12) of Table 8. The estimated effect of the CBEC pilot zone policy on air quality was statistically significant in cities with lower environmental regulation intensity, but insignificant in cities with higher regulation intensity. This indicates that the environmental benefits of the policy are more pronounced in settings with initially weaker environmental regulation, where the policy appears to exert a stronger mitigating effect on air pollution.

This pattern can be explained as follows. In cities with higher environmental regulatory intensity, enterprises have long been subject to stringent environmental constraints and may already have implemented considerable end-of-pipe treatment technologies or preliminary clean production processes. As a result, the marginal cost of further pollution reduction is relatively high, leaving limited room for additional emission cuts. In such contexts, a newly introduced CBEC pilot zone policy—even if it incorporates green trade and logistics requirements—may yield only a limited "superimposition effect" or "incremental impact" when layered on top of already strict environmental controls. By contrast, in cities with lower environmental regulatory intensity, enterprises operate under more lenient environmental constraints and may have higher baseline emissions. In these settings, the introduction of the CBEC pilot zone policy not only facilitates trade but may also establish green standards and introduce advanced environmental technologies, thereby creating an effective "incremental" regulatory environment. This can motivate enterprises to initiate pollution control efforts and pursue green transformation, leading to more substantial marginal improvements in environmental performance.

4.5. Mechanism testing

Given the ongoing debate regarding the applicability of mediation-effect models in economic research—particularly concerns about endogeneity bias and the ambiguous identification of causal pathways[55]—this study followed the approach of Chen and Xie[56] to examine mechanisms. Specifically, we tested whether establishing CBEC pilot zones influences the proposed mechanism variables, which, in turn, may affect air quality. Theoretical analysis posited that CBEC enhances urban air quality through three channels: green technology innovation, productive services industry agglomeration, and resource allocation optimization. First, advances in green technology help cities transform traditional production methods, enhance energy efficiency, reduce energy consumption, accelerate clean energy adoption, and optimize energy consumption patterns, thereby mitigating air pollution. Second, productive service industry agglomeration provides manufacturing with high-value-added, high-tech, low-energy, and low-pollution services, facilitating green transformation. This agglomeration also fosters production specialization, expands capital- and knowledge-intensive activities, generates economies of scale and resource-sharing effects, improves factor productivity, lowers unit energy consumption and pollution emissions, and ultimately contributes to better air quality. Third, resource allocation optimization not only accelerates the cross-regional flow of traditional factors but also fosters integration between traditional and data factors. This enhances factor productivity and reduces undesirable outputs in manufacturing, thereby effectively alleviating air pollution. To empirically test these channels, we estimated the following econometric model, as shown in **Equation 6**:

$$Mech_{it} = \beta_0 + \beta_1 Policy_{it} + \beta_2 Controls_{it} + \delta_i + \mu_t + \varepsilon_{it} \quad (6)$$

where $Mech_{it}$ represents the mechanism variables, including green technology innovation ($Greentec$), resource allocation efficiency (Ra), and productive services industry agglomeration ($Psia$). Due to missing employment data after 2020 in the calculation of productive services, the number of observations for this variable was reduced.

The regression results are presented in Table 9. Columns (1) and (2) show that the establishment of CBEC pilot zones had a significant positive effect on green technology innovation. By promoting green technology R&D and application, these pilot zones help cities reduce energy consumption, improve energy efficiency, and optimize energy structures.[39] Such innovations not only facilitate economic green transformation but also directly enhance urban air quality.[57] Specifically, green technology innovations improve energy efficiency, reduce pollutant emissions, and lower ambient pollution concentrations, confirming H_2.

Columns (3) and (4) indicate that the establishment of CBEC pilot zones significantly improved resource allocation efficiency. On the one hand, optimized allocation makes the distribution of production factors more rational, thereby raising factor productivity.[58] On the other hand, higher allocation efficiency makes production processes more efficient and reduces undesirable outputs.[59] These improvements help mitigate air pollution and enhance air quality, supporting H_3.

According to Columns (5) and (6), the establishment of CBEC pilot zones significantly promoted productive service industry agglomeration. Such agglomeration generates economies of scale and facilitates resource sharing, which elevates overall factor productivity.[60] Moreover, agglomeration enhances energy utilization efficiency, reduces unit energy consumption, and lowers pollutant emissions.[61] These agglomeration effects further improve urban air quality by strengthening industrial chain collaboration,[62] thereby validating H_4.

In summary, the results suggest that establishing CBEC pilot zones indirectly improves urban air quality through green technology innovation, resource allocation, and productive service industry agglomeration. This underscores the multi-dimensional role of CBEC as a policy tool in fostering urban economic transformation and green development. CBEC pilot zones not only expand market opportunities for enterprises but also provide a platform for technological innovation, resource optimization, and industrial agglomeration. A caveat was that missing employment data after 2020 for productive service industry agglomeration might reduce sample size and affect the stability and representativeness of the estimates. Future research could employ more comprehensive datasets to further verify the robustness and long-term effects of these mechanisms. Overall, the CBEC pilot zone policy offers Chinese cities a multi-faceted pathway to simultaneously advance economic and environmental objectives, particularly air quality improvement. These findings provide valuable insights for policymakers seeking to harmonize high-quality economic growth with environmental sustainability.

Table 9. Mechanism test results

Variables	***Greentec***		***Ra***		***Psia***	
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Policy	0.260*** (9.01)	0.186*** (6.74)	0.007* (1.46)	0.009* (1.68)	0.071*** (3.15)	0.084*** (3.84)
Controls	No	Yes	No	Yes	No	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.871	0.893	0.781	0.769	0.845	0.848
Obs	3,962	3,962	3,880	3,880	3,115	3,115

Notes: Standard errors clustered at the city level are reported in parentheses. * and *** indicate significance at the 10% and 1% significance levels, respectively.
Abbreviations: FE: Fixed Effects; Obs: Observations.

5. Conclusion

This study employed panel data from 284 Chinese cities over the period 2009–2022, treating the establishment of CBEC pilot zones as a quasi-natural experiment. It empirically investigated the effect of the CBEC pilot zone policy on urban air quality and examined the mechanisms and heterogeneity underlying it. The main findings are as follows:

(i) CBEC pilot zone policy significantly improved urban air quality, with a particularly notable reduction in per capita SO_2 emissions. After controlling for relevant variables, the policy led to an average decrease of approximately 14.3% in $lnso_2$ and about 16.7% in $lnpso_2$ in pilot cities. These results are robust to a series of robustness tests. A further comparative assessment revealed the substantial real-world relevance of the CBEC pilot zone policy's emission-reduction effect. During the same period, key national environmental regulations, represented by the *Air Pollution Prevention and Control Action Plan*, achieved reductions in urban SO_2 emissions of 15% to 25%. The 14.3% reduction attributable to CBEC corresponds to 60–95% of the average effect of those targeted environmental policies. This indicates that CBEC serves not only as an instrument of trade innovation but also as a meaningful policy tool for advancing environmental governance.

(ii) Heterogeneity analysis showed that the emission-reduction effect of the CBEC pilot zone policy was more pronounced in eastern cities, in cities with better digital infrastructure, and in cities with relatively weaker environmental regulations. This finding also raises concerns about potential regional inequity: if the environmental benefits of CBEC are largely concentrated in eastern regions with stronger digital foundations, while central and western regions lag due to inadequate infrastructure and institutional capacity, merely expanding the pilot zones could exacerbate interregional environmental inequality. Therefore, policy implementation should emphasize regional balance by strengthening digital infrastructure and capacity building in central and western regions, thereby preventing the "digital divide" from translating into a "green divide."

(iii) Mechanism analysis confirmed that the CBEC pilot zone policy mitigates urban air pollution and enhances air quality through three channels: green technology innovation, productive service industry agglomeration, and resource allocation.

Based on these findings, the study proposes the following policy recommendations to further harness the positive role of CBEC in advancing urban green development and air quality improvement:

(i) Integrate CBEC into a coordinated policy framework that simultaneously promotes environmental governance and high-quality development. This study corroborates that CBEC can drive economic growth while reducing pollution, highlighting its potential as a key lever for green transformation. It is advisable to deepen institutional reforms within CBEC pilot zones, cultivate CBEC-enabled industrial clusters rooted in local comparative advantages, facilitate green industrial upgrading, and enhance resource allocation efficiency through CBEC's platform-based integration functions—ultimately achieving a synergy between economic and ecological benefits.

(ii) Adopt differentiated and inclusive region-specific promotion strategies. Given the significant regional variation in CBEC's environmental effects, policy design should be tailored to local conditions, accounting for resource endowments, digital readiness, and environmental regulatory stringency. Greater emphasis should be placed on capacity building and policy support in central and western regions and in cities with weaker digital infrastructure, avoiding a one-size-fits-all replication of eastern experiences. This will help ensure that the environmental benefits of CBEC are equitably distributed across regions.

(iii) Accelerate the development of digital infrastructure to solidify the enabling conditions for CBEC's green development. The national strategy to build a strong digital economy should be fully implemented, with a focus on improving the quality and efficiency of internet coverage. Increased investment in new digital infrastructure—especially in central and western regions and rural areas—will improve broadband connectivity, narrow the digital divide, and provide a solid foundation for CBEC to generate environmental co-benefits.

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Conflict of interest

The authors declare they have no competing interests.

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Availability of data

Data are available from the corresponding author upon reasonable request.

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