frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 24 November 2025
DOI 10.3389/fenvs.2025.1685581

OPEN ACCESS

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RECEIVED 18 August 2025
REVISED 20 October 2025
ACCEPTED 28 October 2025
PUBLISHED 24 November 2025

CITATION
Wang R, Feng F, Khalid Z and Nisar U (2025) China's urban agglomerations as drivers of synergistic pollution and carbon reduction. *Front. Environ. Sci.* 13:1685581. doi: 10.3389/fenvs.2025.1685581

China's urban agglomerations as drivers of synergistic pollution and carbon reduction

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Introduction: This study investigates the impact of China's national-level city cluster policy on the synergistic governance of urban pollution reduction and carbon reduction, focusing on both "quantity reduction" (PM2.5 and CO_2 emissions) and "efficiency improvement" (governance effectiveness). The research explores how the policy, as a quasi-natural experiment, contributes to these dual objectives.

Methods: Using panel data from 274 prefecture-level and above cities from 2006 to 2023, the study employs a difference-in-differences (DID) model to estimate the impacts of the policy. Additionally, mediating and moderating effect analyses are incorporated to explore the mechanisms driving the outcomes.

Results: The findings reveal that the city cluster policy significantly reduces PM2.5 concentrations and CO2 emissions in pilot cities, while simultaneously enhancing governance efficiency. Mechanism analysis identifies three main drivers: green technology innovation, knowledge spillovers, and industrial structure upgrading. Heterogeneity tests show that the quantitative effects (e.g., pollution reduction) are stronger in hub cities, while efficiency gains are more pronounced in non-resource-based cities. There are no significant differences between hub and non-hub cities for efficiency, and no significant impact of resource endowment on quantity reduction.

Discussion: This study contributes to the literature in three key ways: (1) it develops a dual-dimensional framework to assess both "quantity reduction" and "efficiency improvement" in pollution and carbon governance; (2) it uncovers the mechanisms through which the city cluster policy operates; and (3) it identifies regional heterogeneity in the policy's effects across different types of cities. The findings underscore the dual benefits of the policy, validate the mediating mechanisms, and highlight the role of regional differences in the outcomes. Policy implications include expanding and institutionalizing the pilot programme, fostering green innovation, and tailoring city cluster development strategies to local conditions.

KEYWORDS

city cluster policy, synergistic governance, pollution and carbon reduction, DID, green technology innovation

1 Introduction

IPCC's sixth report, Climate Change 2022: Impacts, Adaptation and Vulnerability, warns that both humans and nature are being pushed beyond the limits of adaptation (Martin et al., 2022). Extreme weather patterns and environmental pollution are becoming increasingly prominent, and the consequences of natural disasters, extreme weather events, and species extinctions due to global warming pose significant threats to the Earth's ecosystem and human welfare (Cai et al., 2017). According to recent global carbon data, CO_2 emissions in 2024 reached 11.295 billion tonnes in one major emitter, accounting for over 31% of the global total[1]. While many cities have met national air quality standards for $PM_{2.5}$ in recent years, average concentrations still far exceed the WHO guideline of 10 μg/m^3 (Vandeninden et al., 2025).

In response to these environmental challenges, China has set a "dual-carbon" strategic goal (Liu et al., 2022) to combat ecological degradation and achieve carbon neutrality (Meng et al., 2023). This goal is pursued through the promotion of pollution rights trading (PRT) and carbon emissions trading (CET) policies. However, Li et al. (2016) argued that environmental policies have often been ineffective due to factors such as economic cycles and policy design limitations (Wang et al., 2021). While these policies have mitigated environmental pollution and carbon emissions, they often come at the expense of economic development and social welfare. This has created a policy dilemma, where governments must balance environmental regulation with economic growth. Recent studies highlight how societal wellbeing and policy design are increasingly intertwined with environmental governance, emphasizing the need for integrated, multi-objective frameworks (Hong et al., 2024).

China's urban agglomerations have emerged as a critical strategy for addressing these challenges. Urban clusters are central to urban planning and infrastructure development, promoting social interactions and resource optimization across cities (Qian et al., 2023). Since the introduction of the 11th Five-Year Plan in 2006, China's urban agglomeration strategy has evolved from broad regional coordination based on the "four major sectors" to a more refined, city cluster-based approach that promotes "mutual support growth poles" (Si J. et al., 2024). This shift in policy has led to the gradual construction of a coordinated regional development system based on urban clusters. These clusters are characterized by dense transport networks and frequent exchanges of population, materials, energy, and information, fostering regional integration and development (Fang and Yu, 2017; Wang et al., 2025b). The strategic importance of urban agglomerations in environmental performance has been increasingly emphasized, particularly in urban microclimate studies (Chen et al., 2025).

As of 18 February 2019, the State Council approved 10 national-level city clusters, including the Yangtze River Delta, Harbin-Changsha, Chengdu-Chongqing, and Central Plains city clusters (Cheng and Ding, 2025). The Implementation Plan for Pollution Reduction, Carbon Reduction, and Synergistic Efficiency (PRCCE), jointly issued in 2022 by the Ministry of Ecology and Environment (MOE) (Yang X. et al., 2025) and seven other departments, stresses the importance of exploring effective models for synergistic pollution reduction and carbon reduction within these key city clusters. The establishment of urban agglomerations promotes the free flow of capital, technology, talent, and other resources across regions, enabling cities to reduce pollution and carbon emissions more efficiently (Wu and Xu, 2025).

Thus, exploring the influence of urban agglomeration construction on pollution reduction and carbon reduction, focusing on both the "quantity" and "efficiency" dimensions, holds both theoretical and practical significance. This aligns with contemporary governance perspectives advocating for integrated environmental frameworks at the regional scale (Xu, 2025).

This study investigates whether the construction of urban agglomerations in China promotes the synergistic reduction of air pollution and carbon emissions by combining the dimensions of "quantity reduction" and "efficiency improvement" within a unified analytical framework. The study also explores the mechanisms by which urban agglomerations influence pollution and carbon reduction, using carbon and air pollution emissions as key variables. The study aims to provide insights into pathways for pollution reduction and carbon reduction at the city level. Using data from 274 prefecture-level cities spanning 2006 to 2023, this study treats Chinese urban agglomerations as a quasi-natural experiment and employs a multi-period difference-in-differences (DID) model to estimate the synergistic effects of pollution and carbon reduction.

This study makes three main contributions. First, it constructs a dual-dimensional assessment framework that evaluates both the quantity reduction and efficiency improvement of synergistic pollution and carbon governance. Second, it uncovers the mechanisms through which city cluster policies influence these outcomes. Finally, it identifies heterogeneous effects of the policy across different city types. The findings underscore the dual promotion effects of the policy, the validity of the mediating mechanisms, and the regional differences in policy impact.

Figure 1 illustrates the overall research framework. The study begins with theoretical framework construction and hypothesis development, followed by variable selection and model specification. Urban agglomeration is examined as the core policy variable influencing synergistic pollution and carbon reduction through three mediating pathways: green technology innovation, knowledge spillover, and industrial structure upgrading. The DID model identifies direct effects, while mediation and heterogeneity analyses further explain indirect and differentiated impacts. The final steps synthesize the conclusions and propose targeted policy recommendations.

2 Literature review

Academics have conducted extensive research on the synergistic management of pollution reduction and carbon reduction, with a focus on measurement methods and influencing factors (Yang Y. et al., 2025). The concept of synergistic effects was first proposed by German physicist Haken (1977), who argued that the collective effect of system elements interacting is greater than the sum of their individual effects (Haken and Portugali, 2021). As research on the

1 Source (Carbon Monitor data: https://www.carbonmonitor.org.cn/).

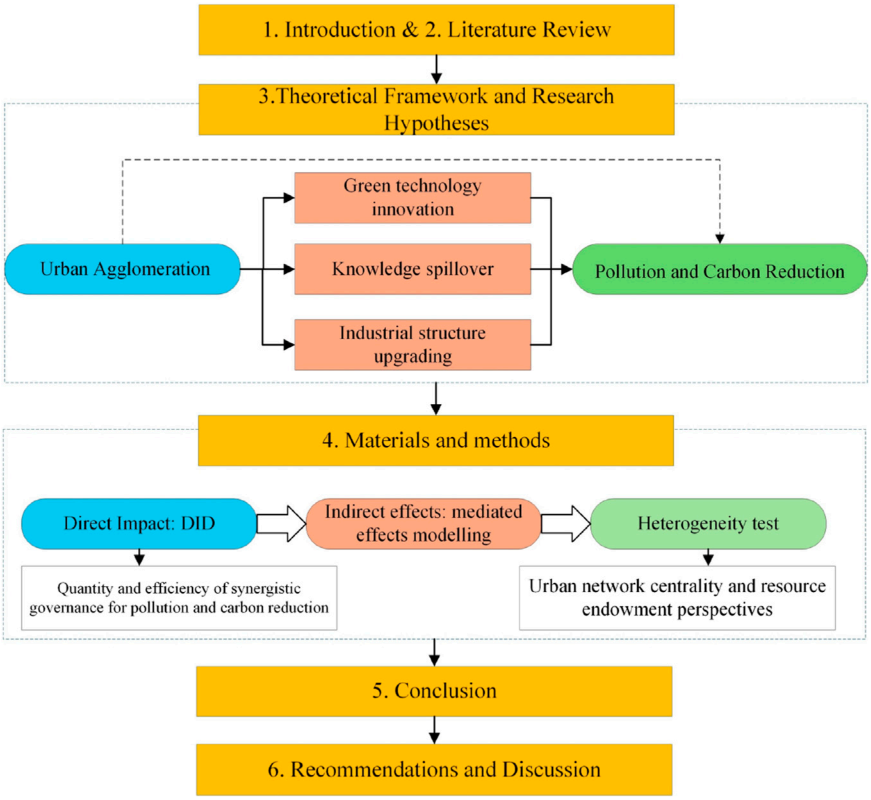

FIGURE 1
Structure of the study.

synergistic management of pollution reduction and carbon reduction deepened, the synergistic effect came to represent "Pareto improvement" or "Pareto optimality," a state in which multiple goals—such as reducing pollution and carbon emissions—are achieved simultaneously (Wang et al., 2025a).

The measurement of synergistic effects in pollution reduction and carbon reduction is typically classified into single-factor indicators and multi-factor indicators. Single-factor indicators often focus on the average concentration of CO_2 and atmospheric pollutants (Zhang et al., 2022), which are simple to measure and understand, but they fail to capture the full scope of synergistic effects. In contrast, some scholars use combinations of multiple indicators to better reflect the synergistic level of pollution and carbon reduction, applying relevant models and methods (Wu et al., 2021; Liu et al., 2023; Nie and Lee, 2023). For example, Wu et al. (2015) assessed the energy efficiency of 30 regions in China using a two-stage network framework. More recently, time-series predictive models and computational intelligence techniques have been applied to environmental issues (Wu et al., 2025; Liu et al., 2024), demonstrating the evolving methodological approaches in synergy measurement. Additionally, recent research highlights the significant role of institutional quality and governance in shaping environmental and distributional outcomes, such as the impact of judicial quality on ecological governance and urban–rural income gaps (Wen et al., 2025).

Regarding the impact of urban agglomeration policies on pollution and carbon reduction, existing studies primarily discuss the environmental governance effects and the dynamic evolution of pollution and carbon reduction in city clusters. Some scholars assert that urban cluster policies can enhance regional connectivity, leading to the transfer of pollution-intensive industries and pollution control technologies from central cities to peripheral regions, thereby reducing $PM_{2.5}$ emissions by strengthening industrial agglomeration effects, driving technological innovation, and reducing resource mismatch (Jiang et al., 2022) and promoting carbon emission reduction in local areas (Xu et al., 2023). However, other studies suggest that the impact of urban agglomeration on pollution emissions follows an inverted U-shaped relationship, with pollution reduction only occurring after a certain threshold is reached (Zhang et al., 2020). This view highlights the organizational and contextual contingencies that influence policy effectiveness, where systemic interactions may either enhance or hinder the desired environmental outcomes (Xi et al., 2025).

Recent work in the construction sector also demonstrates the efficiency of waste and carbon reduction using improved three-stage SBM-DEA models, illustrating the potential for multi-dimensional evaluation approaches in environmental governance (Wang et al., 2024). As urban agglomerations are significant centers of human activity, urbanization, and industrialization, they tend to exhibit high levels of air pollution and carbon emissions. Scholars have examined specific urban agglomerations such as the Pearl River Delta (Chen et al., 2023a), Yellow River Basin (Chen et al., 2023b), and Bohai Rim (Han et al., 2024), focusing on the temporal changes and spatial patterns of pollution and carbon reduction. However, public perception and willingness to engage in sustainable environmental behavior also play a critical role in determining governance outcomes (Zhou et al., 2025).

Recent research on spatial correlation networks and the driving factors of economic resilience provides new insights into how interconnected systems influence environmental outcomes (Wang et al., 2025a). Additionally, studies on the evolution trajectory and driving mechanisms behind construction waste and carbon reduction synergy provide valuable perspectives for understanding the dynamics of policy diffusion and path dependence (Wang et al., 2025b). Despite these efforts, no studies have systematically examined the causal relationship between the construction of urban agglomerations and synergistic pollution-carbon management mechanisms on a national scale.

In terms of research perspectives, much of the existing literature primarily focuses on CO_2 and pollutant emission concentrations. However, based on the "dual-control" policy framework, we assess both the "quantity" and "efficiency" of pollution reduction and carbon reduction. While there are studies indicating decreasing emissions in typical urban agglomerations such as Beijing-Tianjin-Hebei, the Yangtze River Delta, and the Pearl River Delta, the mechanism through which city cluster policies promote synergistic management of pollution and carbon reduction remains underexplored. This paper, therefore, constructs a quasi-natural experiment based on pilot city clusters in China. It innovatively introduces three mediating variables—knowledge spillover, industrial structure upgrading, and green technological innovation—and two moderating variables—green finance and digital infrastructure—to explore how city cluster construction influences the synergistic governance of urban pollution and carbon reduction.

3 Theoretical framework and research hypotheses

As Urban agglomerations, as an important strategy for regional economic development, generate positive externalities for urban pollution reduction and carbon reduction through their unique polycentric and networked spatial structure (Jin and Xu, 2024). The construction of urban agglomerations facilitates the efficient allocation and flow of critical regional factors, such as capital, information, and technology (Liu et al., 2020), enabling the greening and decarbonization of energy use, and enhancing the coordination of pollution prevention and climate governance. Furthermore, urban agglomerations contribute to improving transport infrastructure (Fang and Yu, 2017). By replacing traditional high-pollution transport modes with greener alternatives like high-speed rail, enhancing public transportation networks, and promoting shared travel systems, urban agglomerations can significantly reduce traffic-related pollution and emissions.

The construction of urban agglomerations also promotes intergovernmental cooperation by strengthening cooperative governance across administrative regions. This leads to the establishment of networked monitoring platforms for pollution control and carbon emissions, facilitating real-time monitoring of pollution sources and avoiding "information islands." Moreover, the rapid economic growth spurred by regional integration helps to harmonize environmental regulations and policies across cities, providing financial transfers to assist less developed regions in reducing pollution and emissions.

Hypothesis 1: The construction of urban agglomerations promotes the synergistic governance of urban pollution reduction and carbon reduction.

The construction of urban agglomerations fosters knowledge spillovers (Hong et al., 2019). City clusters, as the central spatial units of regional development, promote the agglomeration of population resources and the generation and diffusion of knowledge and ideas (Deng and Song, 2025). Urban agglomerations break geographical barriers and allow the rapid flow of knowledge-intensive resources, including talents and technologies (Peng et al., 2022). This facilitates the spillover of knowledge and technology through the principle of "learning by doing," which drives R&D upgrading and technological innovation in neighboring enterprises and industries, thus enhancing regional innovation. The spillover of knowledge also reduces production costs, improves resource efficiency, and boosts carbon productivity (Khurshid et al., 2024). Furthermore, the dense social networks in urban agglomerations improve information dissemination and the mobilization of people, which accelerates green knowledge diffusion through social media, community activities, and public welfare campaigns (Cao et al., 2023). This increased awareness promotes public participation in low-carbon and environmentally friendly behaviors, leading to significant reductions in carbon and pollutant emissions.

Secondly, green technological innovation is further promoted within urban agglomerations. The dense network of innovation hubs, including R&D institutions, colleges, and research centers, facilitates the exchange and sharing of resources critical for green technology development (Xia et al., 2025). Core cities in agglomerations act as innovation highlands, driving technological advancements and leading the way in adopting cleaner production processes (Gao et al., 2022; Du et al., 2021). Governments within urban agglomerations also intensify environmental regulation, which, according to the Porter Hypothesis, stimulates green innovation in response to stricter environmental policies (Porter, 1991).

Lastly, urban agglomerations support industrial structure upgrading, which improves energy efficiency and reduces pollution and carbon emissions (Xue et al., 2022). The agglomeration of industries in city clusters attracts investments and technological resources that facilitate the transformation of traditional industries into high-end manufacturing and knowledge-intensive sectors (Umar and Safi, 2023). Moreover, the synergistic effect of industrial upgrading improves the quality and efficiency of industrial clusters, driving greater industrial coordination (Liu and He, 2024). The upgrading of industrial structure encourages the shift from high-pollution industries to low-carbon, high-efficiency sectors such as information technology, biotechnology, and new energy (Wu et al., 2024). These transformations not only reduce pollution but also stimulate green production and green products, further contributing to the goal of pollution and carbon reduction.

Hypothesis 2: Urban agglomeration construction promotes synergistic pollution and carbon reduction through knowledge spillover, green technology innovation, and industrial upgrading.

4 Materials and methods

4.1 Model specification

To identify the impact of national-level city cluster policies on synergistic pollution and carbon reduction, this study treats the policy implementation as a quasi-natural experiment. Currently, the State Council has approved ten national-level city clusters, including the Yangtze River Delta, Pearl River Delta, Chengdu–Chongqing, and the Triangle of Central China. Among them, the national-level city cluster policies were gradually introduced between 2015 and 2019[2]. In this study, prefecture-level cities within these approved national city clusters are defined as the treatment group, while prefecture-level cities outside the clusters constitute the control group. After excluding cities with incomplete data or missing variables, the treatment group contains 152 prefecture-level cities.

Following the approach of Gao and Yuan (2021), a multi-period difference-in-differences (DID) model is employed to evaluate the policy effect. This method effectively captures both time-varying and cross-sectional variations in policy exposure, thereby improving causal inference and reducing potential biases. The basic econometric model is specified as follows:

$$Pol_{it} = \alpha_0 + \alpha_1 DID_{it} + \alpha_2 X_{it} + \mu_{it} + \lambda_{it} + \varepsilon_{it} \tag{1}$$

where Pol_{it} is in the model, Pol_{it} represents the outcome variable for city i in year t. It is measured in two dimensions: **Quantity indicators**, including $PM_{2.5}$ concentrations and CO_2 emissions, which capture the scale of pollution and carbon emissions; and **Efficiency indicators**, which measure synergistic governance efficiency derived from DEA/SFA methods.

DID_{it} is the **policy exposure variable**, equal to **1** for cities located within national-level urban agglomerations during the years when the policy is implemented, and **0** otherwise. X_{it} denotes a vector of **time-varying city-level control variables**, including GDP *per capita*, industrial structure, and energy mix, to account for economic and structural differences across cities. μ_i represents **city fixed effects**, controlling for unobserved, time-invariant characteristics across cities, while λ_t represents **year fixed effects**, capturing common macroeconomic and environmental shocks over time. ε_{it} is the idiosyncratic error term. α_0 is the intercept, α_2 represents the coefficients on the control variables, and α_1 is the key coefficient of interest, which identifies the **average treatment effect on the treated (ATT)** of the national urban agglomeration policy on Pol_{it}, conditional on controls and fixed effects.

The interpretation of the estimated α_1 is as follows:

- For **quantity outcomes** ($PM_{2.5}$ and CO_2): $\alpha_1 < 0$ indicates that the policy effectively reduces pollution and carbon emissions.
- For **efficiency outcomes**: $\alpha_1 > 0$ indicates that the policy improves synergistic governance efficiency.

To further uncover the **underlying mechanisms** through which urban agglomeration policies influence synergistic governance of pollution reduction and carbon reduction, we construct the mediation model presented in Equation 2.

$$M_{it} = \beta_0 + \beta_1 DID_{it} + \beta_2 X_{it} + \mu_{it} + \lambda_{it} + \varepsilon_{it} \tag{2}$$

where M_{it} denotes the three mediating variables (green technology innovation, knowledge spillover, and industrial structure upgrading), and other interpretations of terms are the same as given in Equation 1.

4.2 Variable selection

4.2.1 Quantity and efficiency of collaborative management of pollution and carbon reduction

$PM_{2.5}$ is a $PM_{2.5}$ is a representative indicator of air pollution in China, and its variation reflects the effectiveness of a city's air pollution control capacity (Yi et al., 2022). CO_2, as the principal component of greenhouse gases, contributes substantially to global warming when excessively emitted. Since both carbon and pollutant emissions share **common roots, sources, and processes**—primarily stemming from fossil fuel combustion (Zhao et al., 2025)—this study defines **synergistic pollution–carbon reduction governance** as the *simultaneous reduction of CO_2 and $PM_{2.5}$ emissions*. The *quantity* of synergistic reduction is expressed through the cross-multiplier of carbon and pollutant emissions, capturing the joint intensity of emission reduction efforts. To further evaluate the *efficiency* dimension, this study adopts the framework of Yang et al. (2022) to construct an **input–output system** for synergistic pollution–carbon reduction efficiency. In this system, **capital stock, urban employment, and energy consumption** serve as inputs; **GDP** is treated as the *desired output*; and **CO_2 and $PM_{2.5}$ emissions** are considered *undesired outputs*. The **super-efficient Slack-Based Measure (SBM) model** is employed to estimate efficiency values, where **capital stock**is calculated using the **perpetual inventory method** (base year 2006), and **GDP** is adjusted to **constant 2006 prices** to ensure comparability over time.

4.2.2 National urban agglomeration

The **core explanatory variable** is whether a city participates in a **national-level city cluster pilot programme**. Based on the list of clusters approved by the **State Council** (as of February 2019), each prefecture-level city is assigned a policy–time indicator. For pilot city i, if the city cluster policy was implemented in year t, the **policy dummy variable** takes the value of **1** for year t and all subsequent years, and **0** otherwise.

4.2.3 Green technology innovation

The number of green patents can accurately reflect the city's green technology innovation capacity (Acs et al., 2002). Patents in

2 The State Council approved the following national-level city clusters in successive years: in 2015, the Middle and Lower Reaches of the Yangtze River City Cluster; in 2016, the Harbin–Changchun Megalopolis, Chengdu–Chongqing City Cluster, Yangtze River Delta City Cluster, and Central Plains City Cluster; in 2017, the Beibu Gulf City Cluster; in 2018, the Guanzhong Plain City Cluster, Hubao–Eyu City Cluster, and West Liaohe Plain City Cluster; and in 2019, the Guangdong–Hong Kong–Macao Greater Bay Area City Cluster.

China are classified under the Patent Law into three categories: invention patents, utility model patents, and design patents. Among these, invention patents are considered the most valuable. This is because they are more likely to represent the actual level of technological advancement. Utility model patents and design patents are generally seen as less indicative of true innovation compared to invention patents. Green technology innovation is measured as the log of granted green invention patent.

4.2.4 Knowledge spillover

The "mobility effect" of information and talent facilitates the effective allocation of resources and reduces the costs associated with pollution control, while the "imitation effect" lowers the learning costs between cities, promoting the reallocation of limited resources towards research and development (R&D) for pollution–carbon synergy and green transformation projects. This study quantifies knowledge spillovers by using the natural logarithm of the product of two variables: the number of students enrolled in general undergraduate colleges within the city and the city's government expenditure on education.

4.2.5 Industrial structure upgrading

City clusters upgrade industrial structure by increasing the share of high-tech and service industries, driving the green transformation of high-energy, high-emission sectors. Their industrial synergy promotes green products, reduces fossil fuel dependence, and cuts CO_2 and $PM_{2.5}$ emissions. Industrial upgrading is measured as: (primary industry share × 1) + (secondary × 2) + (tertiary × 3).

4.2.6 Control variables

Population density (inden): It is measured as the logarithm of the ratio of the resident population to the urban area, since population distribution and density significantly affect regional economic growth and energy consumption patterns.

Urbanization level (urba): It is measured by the ratio of the urban population to the total population, as higher urbanization promotes optimal factor allocation through industrial agglomeration, improves energy efficiency, and reduces emission intensity per unit of GDP.

Urban economic density (city): It is measured as the ratio of GDP to the land area of the administrative region, since higher economic density can enhance production efficiency and green technology adoption, reducing pollution.

Strength of financial support (gov): It is measured by the ratio of general fiscal budget expenditures to regional GDP, as government environmental goals and oversight encourage enterprises to access financial resources for improving environmental management.

Industrialization level (lab): Industrialization level (lab) is measured as the log of industrial enterprises above a designated size, as such production consumes large amounts of coal, oil, and natural gas, generating substantial CO_2 and other pollutants.

4.3 Data source

This study employs panel data from 274 prefecture-level and above cities in China spanning the period 2006 to 2023. Due to data constraints, Hong Kong, Macao, and cities with significant missing data — such as Xiantao, Qianjiang, Tianmen, and the Yanbian Korean Autonomous Prefecture — are excluded from the sample. $PM_{2.5}$ data are obtained from the high-resolution, high-quality $PM_{2.5}$ dataset provided by the National Tibetan Plateau Data Centre (NTPDC), compiled by Wei Jing and Li Zhanqing's research team. Carbon emission data are sourced from the Global Atmospheric Research Emission Database (EDGAR). Other variables are drawn from the Statistical Yearbook of Chinese Cities, the China Economic and Social Big Data Research Platform, and various regional economic and social development bulletins. Missing values are imputed using linear interpolation. The dataset is highly reliable, and descriptive statistics are presented in Table 1.

5 Results and discussion

5.1 Descriptive statistics of key variables

Table 1 presents the descriptive statistics for the main variables used in this study. The DID variable, representing the national urban agglomeration policy, has a mean value of 0.233, indicating that approximately 23% of city-year observations fall within the policy pilot scope. For the two measures of pollution–carbon reduction synergy, the average governance efficiency (xl) is 0.586, with values ranging from 0.0066 to 3.990, suggesting significant variation in performance across cities. The average number of treatments (sl) is 1.597, with a maximum of 23.333, indicating large disparities in policy or management interventions. Among the mediating variables, green technology innovation (zlq) has a mean of 2.326, knowledge spillover (zs) averages 14.330, and industrial structure upgrading (stru) averages 2.289, with relatively low variability. Regarding the control variables, population density (peop) averages 5.745, while the urbanization level (urba) averages 0.539, implying that just over half of the population resides in urban areas on average. City economic density (city) exhibits substantial variation, with values ranging from 0.0009 to 17.329. The industrialization level (lab) averages 6.607, and financial support (gov) averages 0.182, indicating that fiscal expenditure accounts for approximately 18% of GDP on average. These statistics highlight substantial heterogeneity across cities in both the explanatory and control variables, providing a solid foundation for the subsequent econometric analysis.

5.2 Impact of national-level city cluster policy on pollution and carbon reduction

Table 2 presents the baseline regression results on the impact of the national-level city cluster pilot policy on synergistic urban pollution and carbon reduction. In columns (1)–(2), the dependent variable is the quantity of synergistic governance, while in columns (3)–(4), it represents the efficiency of synergistic governance. Across all specifications, with and without control variables, the estimated coefficients of the Difference-in-Differences (DID) remain statistically significant at the 1% level. Specifically, after controlling for other factors, the regression

TABLE 1 Summary of key variables.

Variable name	Variables	Observations	Mean	Standard deviation	Minimum	Maximum
National urban agglomeration	DID	4,932	0.233	0.422	0	1
Pollution and Carbon Reduction Synergy Governance efficiency	xl	4,932	0.586	0.267	0.0066	3.990
Pollution and Carbon Reduction Synergy Number of treatments	sl	4,932	1.597	1.909	0.023	23.333
Green technology innovation	zlq	4,932	3.621	1.904	0	10.084
Knowledge spillover	zs	4,932	14.330	2.072	6.032	20.666
Industrial structure upgrading	stru	4,932	2.289	0.148	1.163	2.846
Population density	peop	4,932	5.745	0.925	0.683	7.881
Level of urbanization	urba	4,932	0.539	0.165	0.115	1
City economic density	city	4,932	0.804	0.315	0.0009	17.329
Industrialization level	lab	4,932	6.607	1.114	2.944	9.842
Financial support	gov	4,932	0.182	0.099	0.042	1.024

TABLE 2 Benchmark regression.

Variables	Quantity		Efficiency	
	(1)	(2)	(3)	(4)
DID	−0.220***(−9.473)	−0.206***(−9.067)	0.432***(31.203)	0.423***(30.118)
Peop		0.007 (0.112)		−0.092**(−2.428)
urba		0.040 (0.274)		−0.108 (−1.451)
city		−0.156***(−3.329)		0.060***(7.365)
lab		0.075***(3.848)		−0.018 (−1.324)
gov		−0.012 (−0.088)		−0.132 (−1.290)
Constant	1.548***(199.737)	1.028**(2.444)	0.585***(133.002)	1.3033***(5.503)
City fixed effect	Yes	Yes	Yes	Yes
Time fixed effect	Yes	Yes	Yes	Yes
Observations	4,932	4,932	4,932	4,932
R^2	0.931	0.933	0.658	0.662

*** and ** denote significance level of parameters at 1% and 5%, respectively. t-values are given in parentheses.

coefficient for the quantity of synergistic governance in pilot cities is −0.2060, while the coefficient for governance efficiency is 0.4238, compared to non-pilot cities. In terms of economic significance, a one standard deviation increase in the pilot policy variable corresponds to a 5.45% reduction in the quantity measure and a 30.58% increase in the efficiency measure.

These results indicate that the national-level city cluster policy significantly enhances synergistic pollution-carbon governance, supporting Hypothesis 1. A possible explanation for this is that the policy dismantles administrative barriers, fosters resource sharing, and encourages inter-city collaboration. Through integrated regional development, city clusters optimize resource distribution, industrial layout, and infrastructure construction. This not only reduces redundant investments and resource wastage but also enhances collaborative environmental governance, improving the effectiveness of pollution and carbon reduction strategies across cities.

5.3 Parallel trend test for policy impact validation

To validate the DID model, it is essential for the parallel trend assumption to hold. This assumption stipulates that, after controlling for observable factors, both the treatment and control groups' pollution-carbon synergy "quantity" and

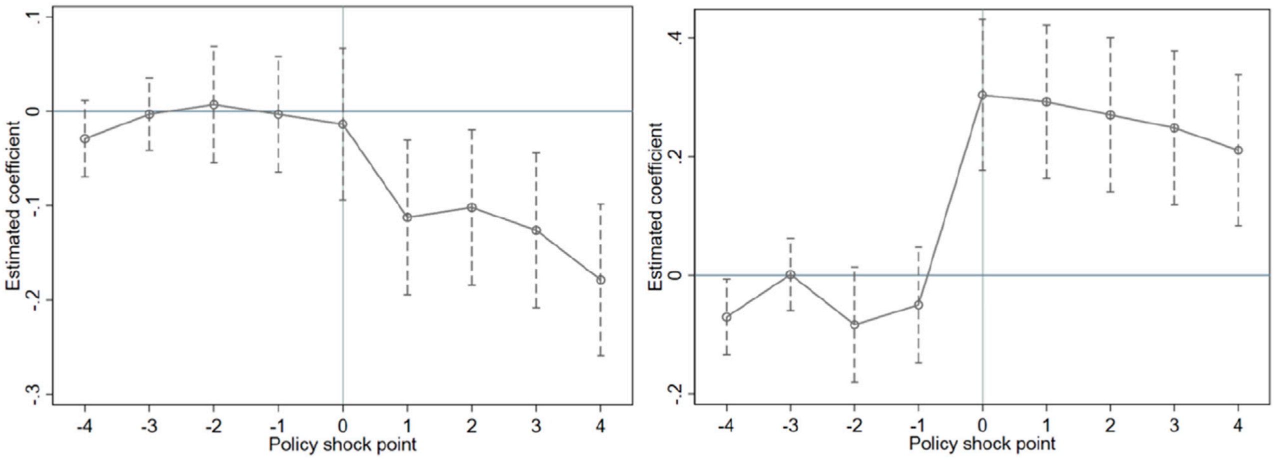

FIGURE 2
Parallel trend test.

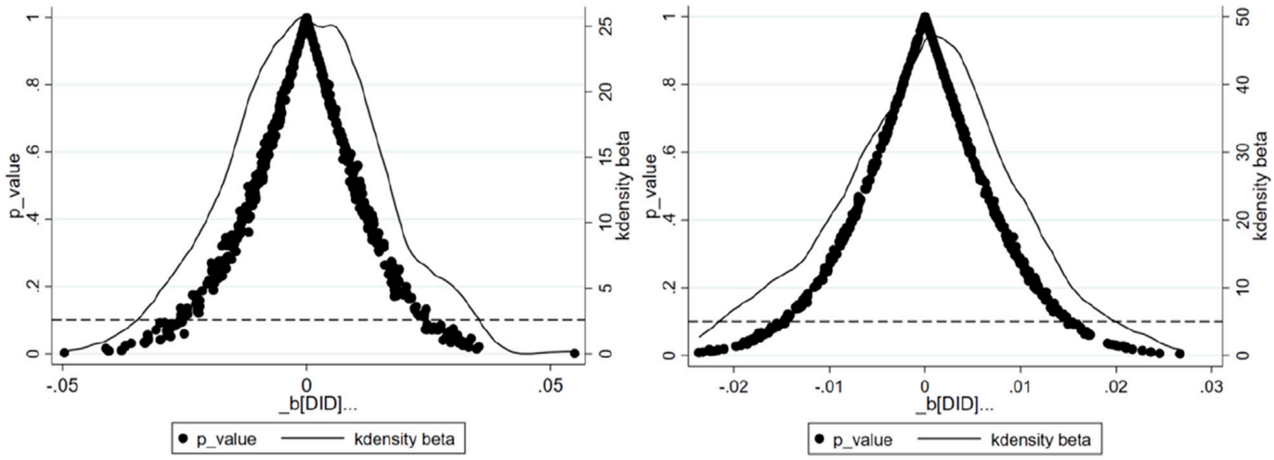

FIGURE 3
Placebo test.

"efficiency" should follow similar trends prior to the policy intervention. To test this, the event study method, as suggested by Bai et al. (2022), is employed. Considering the extended duration of the policy's implementation, the time window is aggregated to cover 4 years before and after the policy intervention. The results are illustrated in Figure 2, where the left panel represents the "quantity" measure and the right panel represents the "efficiency" measure of synergistic governance.

Before the policy was implemented, the estimated coefficients for both measures were statistically insignificant, which suggests that the parallel trend assumption is valid. Following the policy implementation, the coefficient for the "quantity" measure becomes significantly negative, while the coefficient for "efficiency" shows a significant positive change. These results indicate that the national-level city cluster pilot policy has effectively reduced pollution-carbon emissions quantity, while also improving governance efficiency.

5.4 Robustness test

5.4.1 Placebo test (randomized fictitious treatment)

To further assess the robustness of the results, this study follows the methodology outlined by Ferrara et al. (2012) and conducts a placebo test. In this test, a random selection of cities is designated as the "treatment group," presumed to be influenced by the policy, while the remaining cities form the control group. The regression analysis is repeated 500 times, with each iteration using a different randomly selected treatment group. The purpose is to check whether the coefficients of the "pseudo-policy" dummy variables are statistically significant. Figure 3 illustrates the p-values and kernel density distributions for the estimated coefficients of 'quantity' (left) and 'efficiency' (right) in terms of pollution-carbon synergy. The kernel density plots are approximately symmetric around zero, and most coefficients are insignificant at the 10% significance level. This

TABLE 3 Robustness test.

Variables	(1)	(2)	(3)	(4)	(5)
	Quantity	Efficiency	$PM_{2.5}$	CO_2	Coupling coordination
DID	−0.072** (−2.362	0.391*** (21.524	−4.758*** (−20.218	−1.081*** (−3.086	0.031*** (5.897
Constant	0.974 (1.407	1.345*** (2.950	56.156*** (15.115	42.855*** (11.620	1.293*** (16.337
Control variables	Yes	Yes	Yes	Yes	Yes
Citylfixed effect	Yes	Yes	Yes	Yes	Yes
Timelfixed effect	Yes	Yes	Yes	Yes	Yes
Observationsl	3,122	3,122	4,932	4,932	4,932
R^2	0.942	0.667	0.948	0.963	0.638

*** and ** denote significance level of parameters at 1% and 5%, respectively. t-values are given in parentheses.

TABLE 4 Robustness checks: lagged effects, concurrent policy interventions, and exclusion of municipalities directly under the central government.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	Quantity	Efficiency	Quantity	Efficiency	Quantity	Efficiency
DID	−0.234*** (−9.735	0.344*** (21.340	−0.208*** (−9.160	0.420*** (29.866	−0.214*** (−10.215	0.416*** (29.556
Smart City			−0.018 (−0.706	0.016 (1.163		
Low Carbon City			−0.089*** (−3.435	−0.050*** (−3.733		
Constant	0.974** (2.445	0.974*** (5.267	1.156*** (2.691	1.361*** (5.817	1.014** (2.441	1.295*** (5.475
Controllvariables	Yes	Yes	Yes	Yes	Yes	Yes
City fixedleffect	Yes	Yes	Yes	Yes	Yes	Yes
Time fixedleffect	Yes	Yes	Yes	Yes	Yes	Yes
Observationsl	4,658	4,658	4,932	4,932	4,860	4,860
R^2	0.932	0.648	0.933	0.663	0.933	0.657

***, and ** denote significance level of parameters at 1% and 5%, respectively. t-values are given in parentheses.

suggests that the policy effects observed are not attributable to random variation, confirming the robustness of the findings.

5.4.2 Additional robustness test

To mitigate the influence of extreme values and outliers, we conducted additional robustness checks. First, we employed the propensity score matching–difference-in-differences (PSM-DID) method. Given the smaller size of the treatment group and the higher number of matching variables, k-nearest-neighbour matching (k = 2) was applied to preserve information and minimize bias from failed multi-sample matching. The results, presented in columns (1) and (2) of Table 3, show that the estimated coefficients remain statistically significant at both the 5% and 1% levels, and are highly consistent with the baseline regression results in Table 2, thereby reinforcing the credibility of our findings.

Second, we addressed potential concerns over differing calculation methods for the pollution reduction and carbon synergy indicators by replacing the explanatory variables. For the "quantity" measure, PM2.5 emissions and CO_2 emissions were used as alternative indicators, as shown in columns (3) and (4) of Table 3. For "efficiency," we employed the coupled coordination degree model (Liu et al., 2024) to evaluate the synergy after separately calculating carbon emission reduction efficiency and pollutant management efficiency. The results confirm robustness, with urban agglomerations reducing $PM_{2.5}$ by 4.76 μg/m^3 and CO_2 by 1.082 million tonnes, while improving synergy efficiency, consistent with the baseline results.

To further assess the robustness of the findings, several additional tests were conducted. First, we tested for delayed effects by introducing time lags in the explanatory and control variables. The results, reported in columns (1) and (2) of Table 4, show that the policy still significantly improves both the quantity and efficiency of synergy after accounting for time lags, confirming the persistent effects of the policy over time.

Second, we controlled for other concurrent policy interventions to avoid potential bias. Specifically, we included cross-terms between city dummies for the smart city and low-carbon city pilot policies and their approval times in Model (1). The results, presented in columns (3) and (4) of Table 4, show that the DID coefficients remain statistically significant and consistent with the main results, further validating the robustness of the findings.

TABLE 5 Regression results of mechanism analysis for synergistic pollution and carbon reduction.

Variables	DID		
	(1)	(2)	(3)
Green technology innovation	0.035***(4.896)		
Knowledge spillover		0.043***(3.556)	
Industrial structure upgrading			0.660***(8.115)
Constant	−0.634***(-2.809)	−1.082***(−4.104)	−2.023***(−7.228)
Controllvariables	Yes	Yes	Yes
Citylfixed effect	Yes	Yes	Yes
Timelfixed effect	Yes	Yes	Yes
Observationsl	4,932	4,932	4,932
R^2l	0.636	0.635	0.639
Sobel test (Quantity)	0.035***(5.183)	0.023***(3.896)	−0.058*** (−5.977
Sobel test (Efficiency)	−0.010*** (−2.900	−0.014*** (−4.963	−0.007*** (−1.303

*** denotes the significance level of parameters at 1%. t-values are given in parentheses.

Third, we excluded municipalities directly under the central government (Beijing, Shanghai, Tianjin, and Chongqing) from the sample to account for their unique characteristics, such as geographic positioning and specialized economic policies. As shown in columns (5) and (6) of Table 4, the significance and magnitude of the DID coefficients remained largely unchanged from the benchmark regression, further strengthening confidence in the findings.

5.5 Mechanism analysis of pollution−carbon synergy: pathways and robustness tests

This study examines how the national-level city cluster pilot policy influences pollution–carbon synergy through three key mediating channels: green technology innovation, knowledge spillover, and industrial upgrading. Table 5 presents the regression results for each of these pathways. All three variables (columns 1–3) exhibit statistically significant positive coefficients at the 1% level, supporting the theoretical framework and confirming Hypothesis 2. The underlying mechanisms are as follows. First, city clusters act as engines of regional economic growth, concentrating innovation resources and high-tech enterprises. By leveraging policy incentives and market mechanisms, these clusters facilitate the diffusion and adoption of green technologies, enhancing resource efficiency and reducing environmental pressures in production. Second, knowledge spillovers foster the rapid spread of advanced environmental management practices and governance models within the clusters, improving regional synergy and overall governance capacity. Third, industrial structure upgrading accelerates the transition away from high energy-consuming and polluting industries, leading to a significant reduction in both pollution and carbon emissions. The Sobel test, used to assess the robustness of the mediating effects, shows that the mediating effects are statistically significant.

5.6 Heterogeneity analysis of city cluster policy effects on pollution and carbon reduction: resource endowment and urban network centrality

This study investigates the heterogeneous effects of national-level city cluster pilot policies on pollution and carbon reduction, focusing on resource endowment. The analysis divides cities into resource-based and non-resource-based categories[3]to explore the impact of differing resource availabilities on the effectiveness of synergistic governance.

Columns (1) and (2) in Table 6 present results for the “quantity” of pollution and carbon reduction. The estimated coefficients for both resource-based and non-resource-based cities are significantly negative, indicating that the city cluster policy has led to reductions in pollution and carbon emissions for both groups. However, Fisher’s Combined Test yields an empirical p-value of 0.456[4], suggesting no significant difference between the two groups. This indicates that, despite differences in resource endowment, the policy has similarly reduced emissions in both resource and non-resource cities.

The “structural dilemmas” faced by resource cities—such as heavy dependence on high-emission industries—are temporarily alleviated by the strong macroeconomic policy interventions provided by the city cluster policy. Conversely, non-resource cities benefit from their more diversified industrial structures and

3 The sample is divided into non-resource cities and resource cities according to the National Sustainable Development Plan for Resource Cities (2013-2020) issued by the State Council.

4 The empirical P-value was used to test the significance of the coefficients of the differences between groups, which was obtained by sampling 1,000 times based on the Fisher’s Combined Test of bootstrap.

TABLE 6 Heterogeneity analysis of national-level city cluster policy effects by resource endowment on pollution and carbon reduction quantity and efficiency.

Variables	Quantity		Efficiency	
	Resource-based cities	Non-resource-based cities	Resource-based cities	Non-resource-based cities
	(1)	(2)	(3)	(4)
DID	−0.186***(−4.810)	−0.179***(−6.012)	0.311***(14.074)	0.487***(26.587)
Constant	1.985***(4.836)	0.381 (0.581)	1.623***(5.512)	0.945***(2.602)
Controllvariables	Yes	Yes	Yes	Yes
City fixedleffect	Yes	Yes	Yes	Yes
Time fixedleffect	Yes	Yes	Yes	Yes
Observationsl	1980	2,952	1980	2,952
R^2	0.943	0.928	0.634	0.674

*** denotes the significance level of parameters at 1%. t-values are given in parentheses.

TABLE 7 Heterogeneity analysis of national-level city cluster policy effects by urban network centrality.

Variables	Quantity		Efficiency	
	Hub city	Non-hub city	Hub city	Non-hub city
	(1)	(2)	(3)	(4)
DID	−0.517***(−3.605)	−0.159***(−7.553)	0.355***(6.333)	0.419***(28.782)
Constant	−5.633***(−3.166)	1.990***(7.812)	1.747***(2.682)	0.991***(5.128)
Controllvariables	Yesl	Yesl	Yesl	Yesl
City fixedleffect	Yesl	Yesl	Yesl	Yesl
Time fixedleffect	Yesl	Yesl	Yesl	Yesl
Observationsl	342	4,590	342	4,590
R^2	0.936	0.934	0.804	0.650

*** denotes the significance level of parameters at 1%. t-values are given in parentheses.

are better positioned to capitalize on the policy as an “accelerator” for improving their existing systems. This contributes to the non-significant difference in “quantity” effects between the two types of cities.

Columns (3) and (4) show results for the “efficiency” of pollution and carbon reduction. Here, the policy impact is significantly positive at the 1% level for both city types, with an empirical p-value of 0.000. The magnitude of the effects differs, highlighting that non-resource cities benefit more significantly in terms of efficiency gains due to their stronger human capital, dynamic innovation environment, and better financial markets.

The study further examines the impact of urban network centrality on the effectiveness of the national-level city cluster pilot policies, with a focus on the “quantity” and “efficiency” of pollution and carbon reduction. Cities are categorized as “hub cities” or “non-hub cities” based on their network centrality, specifically in relation to transportation infrastructure and connectivity, as outlined in the 2016 Medium and Long-Term Railway Network Plan.

Columns (1) and (2) in Table 7 show the results for the “quantity” of pollution and carbon reduction. Both hub and non-hub cities exhibit significantly negative coefficients, indicating reductions in emissions. However, the coefficient for hub cities is more pronounced, reflecting the stronger impact of the city cluster policy in regions with better connectivity and higher centrality in the network. The empirical p-value of 0.018 indicates a more pronounced quantitative effect in hub cities, suggesting that these cities, with their well-developed transport networks, benefit more from the agglomeration economy, which facilitates the circulation of resources such as technology, information, and talent.

For “efficiency,” columns (3) and (4) show positive coefficients for both hub and non-hub cities, but the difference in the magnitude of the effects is not statistically significant. This indicates that while both city types benefit from improved governance efficiency due to the city cluster policy, the impact is less pronounced in terms of efficiency compared to the “quantity” effect. The diffusion of green technologies and innovation practices from hub cities to non-hub cities helps raise the baseline of governance efficiency across both groups.

6 Discussion

The empirical results confirm that China's national-level urban agglomeration policy has played a crucial role in the synergistic reduction of both pollution and carbon emissions. The study reveals significant improvements in both the quantity and efficiency of pollution–carbon governance, offering a more granular understanding of the policy's effects compared to traditional research.

In terms of quantity reduction, the findings support the growing literature that urban agglomeration policies can substantially lower pollutant and carbon emissions through resource pooling, technological integration, and infrastructure development (Jiang et al., 2022; Liu et al., 2020). The policy's effect on efficiency is also noteworthy. The current study uncovers that the construction of city clusters enhances governance efficiency, which is consistent with the findings of studies that emphasize the role of regional collaboration in improving environmental performance (Wei and Ma, 2024).

The mechanisms driving these outcomes—green technology innovation, knowledge spillovers, and industrial upgrading—align with the academic discourse on innovation-driven environmental improvements. However, our study goes beyond the traditional approach by emphasizing the interconnected nature of these mechanisms. For instance, the 'policy-induced agglomeration economy' created by the city cluster policy enables a virtuous circle where endogenous innovation accelerates, and structural transformation occurs in a seamless, integrated manner. This adds to the work of Wu et al. (2021), who also highlighted how innovation networks foster environmental outcomes, but without emphasizing the linkages between these mechanisms.

The heterogeneity analysis sheds light on how different types of cities respond differently to the policy. The stronger quantity reduction in hub cities confirms the established view that central cities tend to drive regional development (Bo, 2020). Yet, the less significant difference in efficiency improvements between hub and non-hub cities challenges the idea that core cities will always outperform peripheral ones in terms of efficiency gains. This insight points to the broader influence of network centrality and resource endowment, which might have been underexplored in prior studies. The small difference in outcomes between resource-based and non-resource-based cities suggests that the city cluster policy may level the playing field, at least temporarily, by providing macroeconomic support to resource cities facing structural constraints (Si R. et al., 2024).

In particular, the finding that non-resource cities show less marked changes in quantity reduction but a larger improvement in efficiency suggests that these cities are better equipped to harness the policy's benefits in the form of innovation, knowledge diffusion, and technological adaptation (Zheng and Niu, 2023). On the other hand, resource cities with path-dependent industrial structures may face more significant challenges in translating policy benefits into efficiency gains, although they do achieve reductions in emissions (Zheng and Ge, 2022).

Overall, the findings contribute to the growing body of literature on integrated governance and regional collaboration in environmental policy, offering new insights into how city clusters can foster synergies between economic development and environmental protection. This research emphasizes the importance of understanding the nuanced impacts of such policies, not only at the aggregate level but also through the lens of heterogeneity based on city characteristics and network centrality.

7 Conclusion and policy implications

The primary aim of this study was to evaluate the effectiveness of China's national-level urban agglomeration policy in promoting the synergistic governance of urban pollution reduction and carbon reduction. Specifically, the study examined how the policy impacts both the quantity and efficiency of pollution and carbon reductions, and explored the underlying mechanisms driving these effects.

To evaluate the policy's impact, the study employed a Difference-in-Differences (DID) approach with a multi-period design, complemented by event study methods and robustness checks such as placebo tests and PSM-DID. The analysis also included a mechanism analysis to uncover the pathways through which the policy influences pollution–carbon governance, focusing on green technology innovation, knowledge spillovers, and industrial upgrading.

The results of the study show that the national-level urban agglomeration policy significantly reduces $PM_{2.5}$ concentrations and CO_2 emissions in pilot cities, while also improving the efficiency of synergistic pollution–carbon governance. The mechanism analysis revealed that the policy operates through three main pathways: (1) green technology innovation, which optimizes resource use and reduces environmental pressures, (2) knowledge spillovers, which foster regional synergy and improve overall governance capacity, and (3) industrial structure upgrading, which encourages the shift towards greener technologies, leading to a substantial reduction in emissions.

The findings have important policy implications. First, the study suggests maintaining and moderately expanding the pilot program to further strengthen regional collaboration and enhance joint prevention and control mechanisms for air pollution and greenhouse gas emissions. Second, it is recommended that China continue to promote green innovation by improving the mobility of talent, facilitating technology transfer, and incentivizing green R&D across urban agglomerations. Finally, the study underscores the importance of tailoring policies to the specific contexts of different cities—non-resource cities should prioritize clean energy and eco-friendly production, resource-based cities should focus on shifting to low-carbon industries, hub cities should enhance green transport infrastructure, and non-hub cities should improve low-carbon regional connectivity.

This study makes a robust contribution by providing empirical evidence that national-level city cluster policies can reduce pollution and carbon emissions while enhancing governance efficiency. The study also introduces a novel dual-dimensional framework, which distinguishes between the quantity and efficiency of pollution–carbon governance, providing a more nuanced understanding of policy effects. Moreover, by incorporating heterogeneity in the analysis based on resource endowment and network centrality, the study adds depth to existing literature.

Future research could extend these findings by incorporating micro-level data to capture the dynamics of innovation and governance at the firm or local level. Additionally, assessing the long-term effects of city cluster policies would provide valuable insights into their sustainability over time. Cross-country comparisons could also be conducted to identify universal and context-specific drivers of effective urban environmental governance.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

RW: Data curation, Formal Analysis, Methodology, Writing – original draft, Software. FF: Data curation, Conceptualization, Resources, Writing – original draft. ZK: Visualization, Validation, Writing – original draft. UN: Investigation, Resources, Writing – original draft, Data curation.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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