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Catalyzing co-benefits: how cross-regional coordination accelerates pollution and carbon reduction in China's Yangtze river economic belt

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Background: China faces the dual challenge of pollution control and carbon reduction amid rapid urbanization and industrialization, while traditional environmental policies struggle to meet the demands of cross-regional coordinated governance.

Methods: Using the Outline of YREB as a policy context, this study systematically evaluates the co-benefits and mechanisms of cross-regional coordination policies on pollution and carbon reduction. Based on panel data from 259 Chinese prefecture-level cities (2014–2019), we employ a coupling coordination model and a difference-in-differences approach to assess policy effectiveness.

Results: The findings reveal that: (1) Cross-regional coordination policies significantly enhance pollution-carbon synergy in YREB cities through structural integration effects, with the impact strengthening over time and remaining robust across tests; (2) The policy facilitates long-term pollution-carbon synergy governance through three key pathways—industrial green transition (structural), clean energy system co-construction (technological), and cross-regional low-carbon technology diffusion (knowledge-based)—driving a shift in environmental governance from policy-driven external enforcement to development-driven endogenous demand.

Conclusion: This study highlights that cross-regional coordination is not only a tool for spatial economic integration but also a structural driver of sustainable environmental governance, providing a novel policy pathway for China's dual-carbon goals and contributing to global climate governance.

KEYWORDS

cross-regional coordinated development policy, pollution and carbon reduction, co-benefits, Yangtze river economic belt, mechanism analysis

1 Introduction

China is a major nation undergoing rapid urbanization and industrialization, facing two key environmental governance challenges: traditional pollution control and achieving "carbon peak and carbon neutrality." According to the latest 2023 Bulletin on the State of China's Ecology and Environment, only 59.9% of the 339 monitored cities nationwide met the national ambient air quality standards, and the average proportion of days with good air quality was 85.5%, lower than the level of the past 3 years. Although the national average PM2.5 concentration was better than the annual target and has cumulatively declined by 28.6% since the 13th Five-Year Plan period, the critical inflection point from quantitative to qualitative improvement in air quality has yet to be reached. While China has achieved the fastest rate of air quality improvement globally, air pollution control remains in a challenging stage, characterized by the uphill struggle to overcome structural barriers and sustain progress. Meanwhile, under the compounded pressure of achieving the "dual carbon" goals, China bears the formidable responsibility of achieving the largest reduction in carbon emission intensity globally. However, to date, only 38 prefecture-level and above cities have proactively reached their carbon emission peaks (Shan et al., 2022), indicating a lagging overall peaking process. Substantially greater efforts will be required in the future to meet the national carbon neutrality targets. In response to the multi-objective requirements of ecological and environmental governance, the Chinese government has decided to shift its focus toward carbon reduction during the 14th Five-Year Plan period and beyond. This transition prioritizes coordinated pollution and carbon reduction to achieve co-benefits. The government has also set a development goal of significantly enhancing the capacity for coordinated pollution and carbon reduction by 2030. Despite significant progress in pollution control, many regions continue to experience rising carbon emissions (Feng and Fang, 2019), indicating a lack of synergy between pollution reduction and carbon mitigation. This disparity arises from disjointed environmental policies, which tend to address pollution control and carbon reduction as independent goals rather than as part of a cohesive strategy. Since both greenhouse gas emissions and atmospheric contaminants predominantly stem from shared anthropogenic activities—especially the combustion of hydrocarbon-based energy sources (Zhang et al., 2015)—scholars have emphasized the necessity of adopting systemic mitigation frameworks (Alimujiang and Jiang, 2020; Jiang et al., 2021). Decoupling these interconnected issues through fragmented interventions risks triggering counterproductive outcomes, exemplified by scenarios where localized air quality improvements inadvertently exacerbate CO_2 output. Consequently, the strategic integration of emission abatement measures has emerged as a critical pathway for enabling holistic ecological modernization during China's current developmental phase (Yuan et al., 2022; Liang et al., 2024).

Environmental pollution and carbon emissions are not confined within administrative boundaries; instead, they exhibit strong spillover effects, spreading from local to wider regions (Song et al., 2020; Wang et al., 2023). However, China's traditional territorial governance model, where individual regions bear full responsibility for their own environmental management, has proven inadequate in addressing challenges such as cross-regional pollution spillovers, unclear responsibilities, and weak supervision mechanisms (Tang, 2021; Liu and Tan, 2023). These limitations highlight the synergistic benefits of jointly achieving pollution reduction and carbon reduction across multiple regions. The necessity for cross-regional collaboration stems from two key factors. First, carbon emissions are a typical public good, meaning their spillover nature makes pollution-carbon governance a collective action problem. Effective governance requires local governments to move beyond fragmented, isolated efforts ("fighting on their own") toward a cooperative, win-win model (Zeng M. et al., 2023). Second, China's provinces and cities exhibit significant heterogeneity in resource endowments, economic structures, industrial compositions, and technological capacities. Leveraging regional comparative advantages through collaboration can achieve greater environmental efficiency at lower costs (Xu et al., 2024). Unlike developed countries that have already peaked carbon emissions and advanced towards carbon neutrality, China faces tighter timelines, higher costs, and structural imbalances, making the pursuit of synergistic pollution-carbon reduction a pressing challenge. Although cross-regional collaborative governance has been proposed as a solution, it remains unclear whether such policies can effectively enhance pollution-carbon synergy given China's territorial governance framework and regional disparities.

However, the extent to which cross-regional collaboration can effectively foster pollution–carbon synergy depends largely on how well it is institutionalized within broader regional development strategies. The Yangtze River Economic Belt (YREB) exemplifies this transformation. As a vast cross-regional economic initiative spanning China's eastern coastal provinces to its central and western inland areas, the YREB aims not only to promote coordinated economic growth but also—perhaps less explicitly—to serve as a platform for integrating environmental governance into regional integration processes. Cross-regional coordination is inherently complex, involving multiple administrative levels and stakeholders with diverse interests. Yet, economic interdependence among regions creates structural incentives for aligning environmental policies. When regions become economically linked through trade, infrastructure, and investment flows, the cost of environmental externalities becomes shared—encouraging a shift from competitive pollution displacement to joint environmental governance. In this context, coordination is not simply a policy instrument but an evolving institutional force that embeds environmental objectives into the logic of economic cooperation. The Outline of the Development Plan for the Yangtze River Economic Belt (Outline of YREB) emphasizes "ecological priority and green development" as core principles. It proposes building an integrated market system, facilitating cross-regional resource allocation, and fostering innovation-led industrial transformation. As the policy takes effect, the spatial convergence of air pollutants and carbon emissions across regions increases the urgency—and feasibility—of collective action. Through mechanisms such as innovation spillovers, industrial upgrading, and clean energy transitions, cross-regional policies help translate economic coordination into durable environmental outcomes. This study

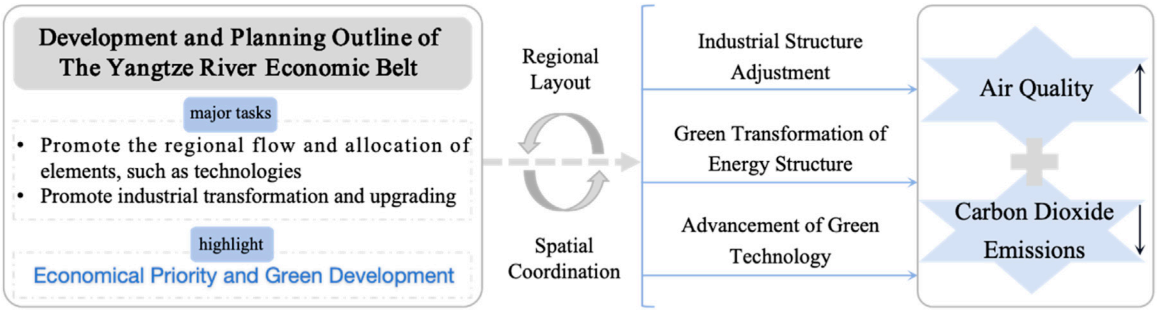

FIGURE 1
Conceptual framework for the impact of inter-regional collaborative development policies on pollution reduction and carbon emission mitigation.

captures these dynamics through a methodological framework (Figure 1) that systematically maps the interrelationships between economic integration, governance complexity, and environmental co-benefits.

Reducing air pollution and carbon dioxide emissions across multiple dimensions requires coordinated efforts at the city level. This involves exploring various emission reduction mechanisms across different city types, enhancing coordination in urban development, production, and daily life, and accelerating the transition toward green, low-carbon cities. This study utilizes panel data from 259 Chinese prefecture-level cities (2014–2019) and applies a combination of the coupling coordination model and the difference-in-differences method to empirically assess the effects of cross-regional cooperation policies on reducing pollution and carbon emissions. It examines whether cross-regional development fosters pollution-carbon synergy, the mechanisms through which regional cooperation influences pollution and carbon reduction, and the policy implications for achieving China's dual carbon goals.

This study makes three key contributions to the literature. First, although prior research on environmental governance has predominantly focused on isolated regulatory instruments targeting single pollutants or achieving short-term environmental outcomes (Fan et al., 2022; Bu et al., 2024), limited attention has been paid to how cross-regional strategic frameworks structurally integrate fragmented governance systems. This study emphasizes the structural integration effect of cross-regional policies, taking the Yangtze River Economic Belt (YREB) strategy as an illustrative case. The YREB strategy achieves governance cohesion through regional interaction mechanisms. By breaking down administrative barriers and coordinating regional interests, it incorporates fragmented environmental governance units into a unified framework, thereby advancing the understanding of macro-level institutional arrangements that transcend administrative fragmentation to enable coordinated pollution and carbon mitigation. Second, although existing literature largely confirms the presence of synergistic effects between pollution reduction and carbon mitigation (Chen X. et al., 2023; Chen Y. et al., 2023; Tang et al., 2025), few studies have systematically identified the regional transformation pathways that underpin such synergy. This study constructs a three-dimensional pathway—comprising industrial green transition (structural dimension), clean energy system development (technological dimension), and low-carbon technology diffusion (knowledge-based dimension)—to explain how cross-regional cooperation aimed at economic development can facilitate synergistic environmental governance. The proposed model offers a replicable and scalable pathway for cross-regional collaboration in addressing complex environmental challenges such as climate adaptation. Finally, while traditional paradigms of environmental governance typically rely on sector-specific regulatory interventions (Zeng W. et al., 2023), this study proposes a sustainable governance mechanism driven by institutional interdependence. It demonstrates how cross-regional policies foster development interdependencies, internalizing environmental objectives into broader frameworks of regional coordinated development. Unlike command-and-control policies that externally regulate specific pollutants, this mechanism promotes governance synergy by cultivating self-sustaining regional interest communities. This perspective provides a novel theoretical explanation for how non-environmental policies can become significant drivers of regional environmental governance, thus moving beyond the conventional view that environmental governance must rely exclusively on dedicated environmental instruments.

The rest of the paper is organized as follows. Section 1 introduces the background surrounding the formulation and implementation of the Outline of YREB. Section 2 constructs the empirical research data for this paper and establishes the econometric regression model. Section 3 presents the empirical findings and conducts tests on the key assumptions for the validity of the empirical model. Section 4 investigates and decomposes the mechanisms through which the cross-regional collaborative development policy impacts pollution and carbon reduction, and Section 5 concludes the paper.

2 Policy background

The Yangtze River Economic Belt (YREB), serving as a vital engine for China's economic development, plays a crucial role not only in regional economic growth but also in advancing the nation's ecological civilization and sustainable development strategy. The YREB encompasses 11 provinces and municipalities in China (see Figure 2), representing 21% of the country's total land area and encompassing over 40% of its population and economic output. In September 2016, the Outline of YREB was officially released as an cross-regional coordinated development policy, serving as a key policy document guiding this national strategy to promote regional development. Grounded in the core principle of "prioritizing ecology and pursuing green development," it provides a strategic framework for sustainable growth in the region. The Outline of

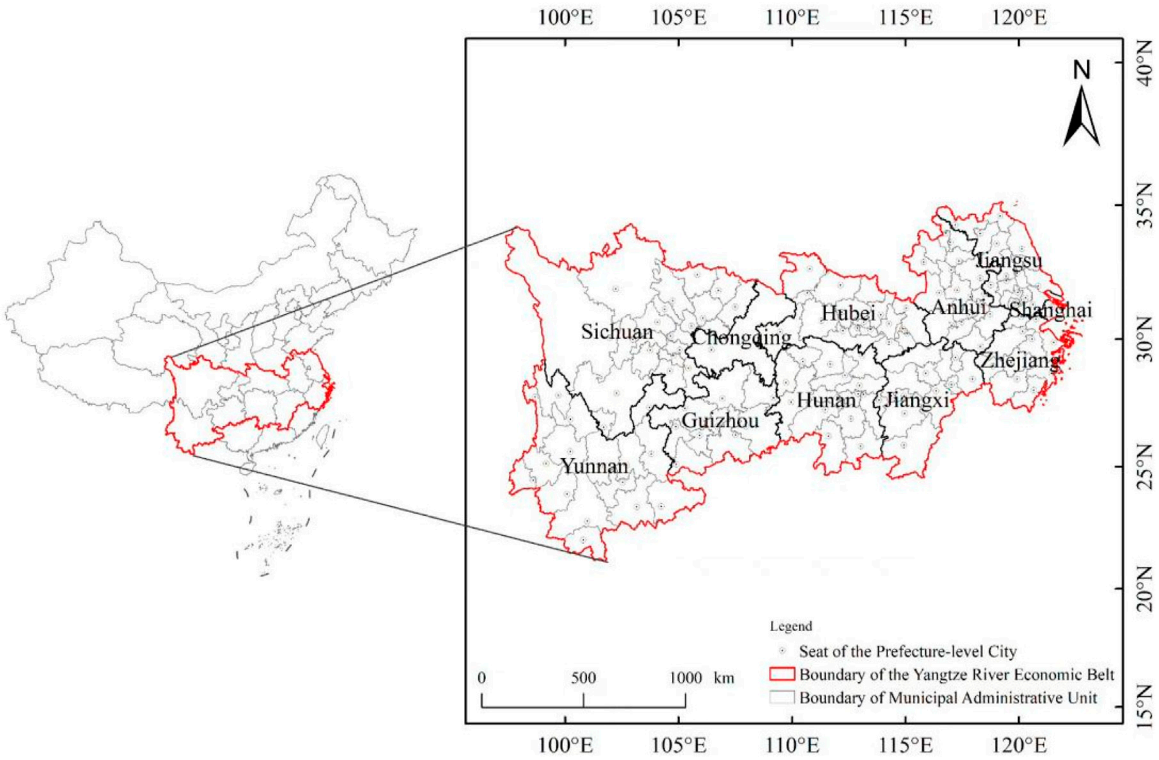

FIGURE 2
Regional map of the Yangtze river economic belt.

YREB requires all provinces and cities to expedite the shift from an extensive development model, progressively eliminate high-energy-consuming industries, and optimize the industrial structure. It calls for the advancement of an integrated market system construction, the establishment of inter-regional market access and mutual recognition systems for quality and qualifications, and the breaking down of regional divisions and industry monopolies. It requires achieving the goal of innovation-driven industrial transformation and upgrading by enhancing independent innovation capabilities, promoting industrial transformation and upgrading, creating core competitive advantages, and guiding the orderly transfer of industries. It advocates for the formation of a new type of urbanization pattern that is regionally linked, structurally rational, intensively efficient, and green and low-carbon, promoting coordinated development of various types of cities and encouraging green travel, thus advancing new urbanization. Through a range of policy initiatives, it promotes the refinement and enhancement of the regional economic structure while fostering the innovation and implementation of green and low-carbon technologies (Zhang et al., 2022).

In the past 8 years, the General Secretary has conducted extensive field research across the upper, middle, and lower sections of the Yangtze River, leading four key symposiums to shape the strategic direction of YREB development. The most recent symposium, held in Nanchang in October 2023, focused on advancing high-quality growth within the YREB. A core emphasis was placed on enhancing regional coordination and fostering integration. Accordingly, provinces and cities along the Yangtze River are expected to strengthen mechanisms for inter-provincial consultation, joint ecological governance, integrated advancement, and shared economic benefits. Hey are encouraged to improve regional traffic connectivity, align policies, standardize regulations, and coordinate implementation to gradually build an ecological and shared-interest community, promoting coordinated regional development.

Despite the implementation of policies facing a series of challenges such as initial costs of technological transformation, the difficulty of traditional industry transition, the stability of clean energy supply, and the coordination of cross-regional policies, "collaboration" remains a key strategy for the YREB. Advancing the development of the YREB is in line with the objective of establishing a sustainable and environmentally friendly growth trajectory. In the context of dual-carbon goals, leveraging the YREB as a spatial economic strategy for China facilitates the integration of regional resources, environment, and transportation across areas with significant developmental disparities. It aims to gradually dismantle administrative divisions and market barriers, facilitate the efficient and free movement of economic factors. Optimize resource allocation, and achieve a unified market integration. Under the impetus of high-level policy, it significantly contributes to enhancing air quality and optimizing the ecological environment in the YREB. Moreover, it serves as an important model and strategic reference for advancing low-carbon development at the national level.

3 Empirical methodology

3.1 Pollution and carbon reduction coupling coordination model

Energy-intensive sectors exhibit characteristics of having the same origin, source, and emission medium for greenhouse gases and most atmospheric pollutants. As a result, there exists a significant dynamic coupling between CO_2 emissions reduction and atmospheric pollution management. The coupling coordination model effectively identifies concurrent collaborative trends among different subsystems while assessing the overall interaction between systems. Rooted in physics and influenced by the coupling degree model (Illingworth, 1991), this approach utilizes the binary system coupling method to quantify the coordination level between efforts aimed at reducing urban pollution and lowering carbon emissions. The corresponding formula is presented below (Equation 1):

$$C = 2\left[\frac{u_1 u_2}{u_1 + u_2}\right]^{\frac{1}{2}} \tag{1}$$

In this framework, a newly introduced variable, T, serves as the comprehensive assessment index, which is determined using the following formulas (Equations 2, 3):

$$T = \alpha u_1 + \beta u_2, \alpha + \beta = 1 \tag{2}$$

$$D = \sqrt{C \times T} \tag{3}$$

The Pollution and Carbon Emission Reduction Coordination and Efficiency Enhancement Plan 2030 primarily aims to drive significant progress in synchronizing carbon peaking efforts with air quality improvements across key regions designated for atmospheric pollution control. To assess this, the annual carbon dioxide emissions (measured in million tons) and the yearly average Air Quality Index (AQI) are denoted as u_1 and u_2, respectively. Drawing on the work of Liu et al. (2021) and their Coupling Coordination Model for Pollution and Carbon Reduction, the plan underscores the equal significance of mitigating both carbon emissions and air pollution. Moreover, the synergy between pollution and carbon reduction exhibits a direct positive correlation with the coordination degree (D value).

3.2 Difference-in-differences estimation

This study aims to explore whether cross-regional collaborative development policies foster synergy between regional pollution reduction and carbon emission mitigation. To evaluate policy impacts, the widely recognized Difference-in-Differences (DID) model is utilized. This method classifies study subjects into two distinct groups: a treatment group, encompassing regions where the policy is implemented, and a control group, consisting of areas where the policy is not applied. By examining variations in trends over time—before and after policy enforcement—and comparing changes between the two groups, the DID model effectively isolates the policy's net impact while controlling for other unobservable time-dependent factors. This analytical approach has been extensively used in policy evaluation research (Cai et al., 2016; Yang et al., 2023). In this research, cities identified in the Outline of YREB constitute the treatment group, whereas other cities serve as the control group. This design facilitates a quantitative assessment of the cross-regional collaborative development policy. The specific model specification is as follows (Equation 4):

$$Y_{cy} = \theta + \mu Treat_c \times Post_y + X_{cy}\varphi + \eta_c + \gamma_y + \varepsilon_{cy} \tag{4}$$

In this context, Y_{cy} denotes the synergy level between pollution mitigation and carbon emission reduction for city c in year y. $Treat_c$ is a dummy variable that indicates whether city c is subject to the cross-regional collaborative development policy. It is assigned a value of 1 if the city is listed in the Outline of YREB, and 0 otherwise. Additionally, $Post_y$ is a time dummy variable distinguishing the periods before and after the policy implementation. It is assigned 1 for years following the release of the Outline of YREB (i.e., post-2016) and 0 for the pre-policy period.

3.2.1 Dependent variable

The dependent variable is constructed using the Coupling Coordination model, which integrates annual carbon dioxide emissions and the Air Quality Index (AQI) to assess the degree of coordination between air pollution control and carbon mitigation. The AQI is a standardized indicator of urban ambient air quality and is widely used in environmental performance evaluations (Zheng et al., 2024). Carbon emissions data, meanwhile, are commonly employed as a proxy for regional carbon mitigation performance in environmental and climate policy studies (Sovacool et al., 2022; Oberthür and Von Homeyer, 2023). The resulting composite index reflects the environmental co-benefits associated with cross-regional coordinated development. The definitions and data sources of all variables used in this study are summarized in Table 1.

3.2.2 Core explanatory variable

The Outline of YREB, which was issued by the national government in 2016. This is represented as an interaction term ($Treat_c \times Post_y$) between group virtual variables (city) and time virtual variables (year). Based on data availability, 98 cities in the YREB were selected as the experimental group. Specifically, when the sample pertains to cities within the YREB and the period falls after the implementation of the policy, $Treat_c \times Post_y$ given a value of 1, and 0 otherwise.

3.2.3 Control variables

To ensure the robustness of the estimation results, the model incorporates two categories of control variables—socioeconomic and meteorological factors—to account for city-level heterogeneity in both anthropogenic activities and natural environmental conditions that may affect pollution-carbon synergy. To control for socioeconomic heterogeneity across cities that may influence environmental outcomes, this study incorporates a set of theoretically grounded and empirically supported Socioeconomic Data. Gross Domestic Product *per capita* (GDPPC), which reflects the level of economic advancement. According to the Environmental Kuznets Curve hypothesis, there is an inverted U-shaped relationship between economic growth and environmental degradation (Grossman and Krueger, 1991; Pata

TABLE 1 Definition and data source of variables.

Variable	Definition	Data source
CO_2	Carbon Dioxide Emissions	China Emission Accounts and Datasets (CEADs)
AQI	Air Quality Index	China Air Quality Online Monitoring Platform
D	Coordination Degree of Pollution Reduction and Carbon Emission Reduction	Calculated from the Coupled Coordinated Model for Pollution Reduction and Carbon Emission Reduction
GDPPC	Per capita GDP	China Urban Statistical Yearbook
PD	Population Density	
GCR	Green Coverage Rate of Built-up Areas	
PRI	The proportion of the primary industry in the regional GDP	
SEC	The proportion of the secondary industry in the regional GDP	
PSTE	Proportion of Scientific and Technological Expenditure	
PEE	Proportion of Education Expenditure	
UR	Urbanization Rate:Urban Resident Population/Total Resident Population	
Meteorolo-gical Data	Annual Total Precipitation (ATP) Mean Air Pressure (MAP) Mean Wind Speed (MWS) Mean Temperature (MT) Mean Relative Humidity (MRH)	China Surface Climate Daily Dataset (V3.0)

TABLE 2 Descriptive statistics of the variables.

Variable	Unit	Observation	Mean	Standard deviation
CO_2	million tones	1,456	1.000	1.465
AQI	—	1,554	1.000	0.273
D	—	1,456	1.099	0.480
Socioeconomic Data				
GDPPC	*per capita* in ten thousand yuan	1,554	6.446	5.73
PD	people per square kilometer	1,554	455.1	357
GCR	%	1,551	40.33	6.075
PRI	%	1,554	12.13	21.89
SEC	%	1,554	44.83	10.09
PSTE	%	1,554	0.308	0.323
PEE	%	1,554	3.36	1.59
UR	%	1,554	57.5	14
Meteorological Data				
ATP	mm	1,554	1,086	589.7
MAP	hpa	1,554	971.8	53.44
MWS	m/s	1,554	2.183	0.48
MT	˚C	1,554	14.78	5.177
MRH	%	1,554	70.01	10.42

et al., 2025). Population density (PD) serves as an indicator of population size dynamics. Human activities play a crucial role in both exacerbating air pollution and contributing to its mitigation (Din et al., 2022). The green coverage rate of built-up areas (GCR) reflects urban ecological conditions, as greening has been shown to absorb pollutants and regulate microclimates (Gaffin et al., 2012). Industrial structure is measured by the shares of the primary (PRI) and secondary (SEC) industries in GDP, both of which are commonly linked to higher levels of energy use and pollutant emissions, thereby imposing greater pressure on environmental systems (Zhang et al., 2021). Technological and human capital factors are proxied by the proportion of scientific and technological expenditure (PSTE) and the proportion of education expenditure (PEE), both of which have been linked to enhanced innovation capacity and long-term environmental governance (Zhang and Yang, 2024). The Urbanization Rate (UR), when increased to a certain extent, is expected to promote energy efficiency and emission reduction (Wu et al., 2024). Meteorological factors significantly influence air pollutant concentrations, with the magnitude and direction of effects varying by pollutant type and region. Wind speed, precipitation, and humidity are generally negatively correlated with pollution levels, whereas atmospheric pressure and temperature tend to exert positive or amplifying effects (Liu et al., 2020). Meteorological data includes annual precipitation, average air pressure, wind speed, temperature, and relative humidity, all of which represent key meteorological-related factors. These meteorological conditions exert a substantial influence on air pollution levels.

This study employs an unbalanced panel dataset covering 259 cities across China from 2014 to 2019. The descriptive statistical results are presented in Table 2. The mean normalization method is applied to standardize the two subsystems of pollution and carbon reduction, ensuring that differences in indicator dispersion are neither underestimated nor overstated. This prevents potential distortions that may arise when using the conversion method to construct the correlation coefficient matrix. Additionally, logarithmic transformation is applied to inverse indicators before the dimensionless treatment, and the reciprocal transformation method is used for positive normalization.

4 Empirical results

4.1 Parallel trend test

The effectiveness of DID approach relies on the parallel trend assumption, which asserts that, in the absence of coordinated regional development policies, the trajectory of collaborative pollution and carbon emission reduction in coordinated cities would align with that of other cities. To verify this assumption, and following the methodology of Jacobson et al. (1993), this study employs an event study analysis to assess the parallel trend. The estimation model is as follows (Equation 5):

$$Y_{cy} = \alpha + \sum_{k=-2}^{k=3} \beta_k \times D_{c,y_0+k} + \gamma_c + \delta_y + \varepsilon_{cy} \tag{5}$$

In the given model, $D_{c,y0+k}$ epresents a set of dummy variables, with y_0 signifying the inaugural year of the cross-regional collaborative development policy for city *c*, and *k* representing the year subsequent to the commencement of the policy. The dataset used in this study spans from 2014 to 2019, covering 2 years prior to the policy implementation and 3 years following its introduction. The focal variable of interest is β_k, which represents the difference in collaborative pollution reduction and carbon emission reduction between the experimental and control groups in the k - th year of policy implementation.

Should the trend of variable β_k exhibit a relatively stable pattern in the interval preceding the policy's implementation, that is, for $k < 0$, this corroborates the parallel trends assumption, signifying that the experimental and control groups were progressing along parallel paths prior to the intervention. In contrast, a pronounced upward or downward trend in the trajectory of β_k during $k < 0$ would indicate a pre-existing significant disparity between the groups, thereby failing to uphold the parallel trends assumption. The trend test outcomes depicted in Figure 3 verify that the research satisfies the parallel trends assumption, with significant effects on pollution mitigation and carbon emission reduction becoming evident by the fourth year after the policy's implementation.

4.2 Difference-in-differences estimation analysis: benchmark model

This study utilizes the Difference-in-Differences (DID) method to evaluate the effects of cross-regional collaborative development policies on pollution and carbon emission reduction. The empirical findings are presented in Table 3. Column (1) accounts for city and time fixed effects, while Columns (2) and (3) further incorporate socioeconomic and meteorological variables, respectively. Column (4) reports results with all control variables included.

The regression outcomes indicate that all estimated coefficients are positive and statistically significant at a minimum of the 10% level, demonstrating that cross-regional collaboration policies have notably strengthened the synergy between pollution and carbon reduction in YREB cities. Specifically, in comparison to cities outside the YREB, the synergy effect (D) of pollution and carbon reduction within the belt has risen by 4.7%. These results suggest that regional collaboration plays a crucial role in enhancing coordination between air pollution management and carbon reduction efforts.

4.3 Robustness tests

4.3.1 Winsorizing

To mitigate the influence of extreme values for certain individual samples in certain years, this study employs the Winsorizing technique (Winsor2 command) on the dependent variable with a bilateral 1% trim, excluding outliers, and then conducts the regression again. As shown in Table 4, Columns (1) and (2), the estimated coefficients for the pollution and carbon reduction policy variables remain statistically significant at the 5% level, aligning with the results of the baseline model.

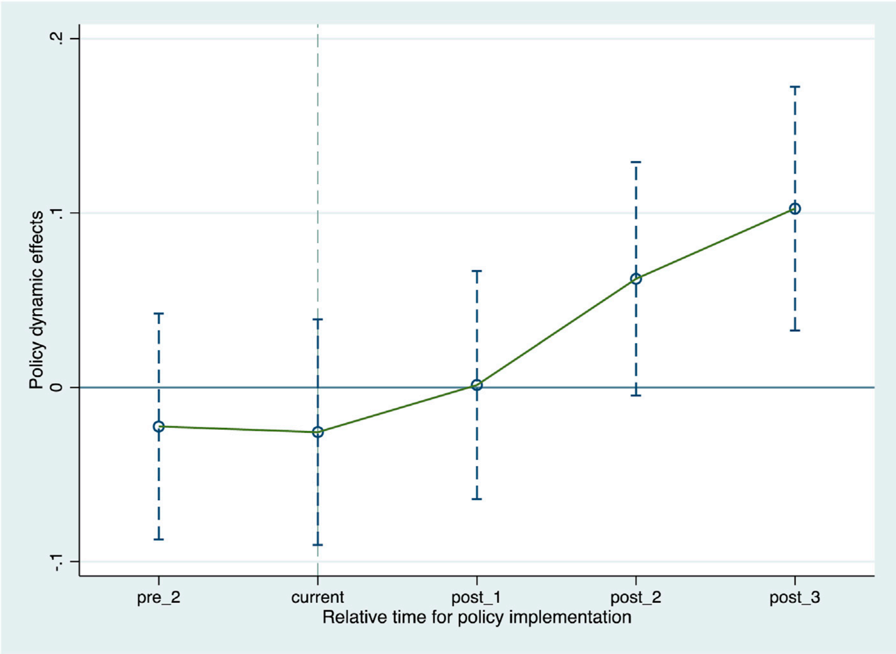

FIGURE 3
Parallel trend test.

4.3.2 Controlling for the impact of other policy changes

The sample period for this study covers 2014 to 2019. During this time, aside from the release of the "Outline of YREB" in 2016, two major policy changes occurred: first, the low-carbon city pilot policy, with the second phase starting in 2013 and the third in 2017, both of which significantly reduced urban air pollution (Yu and Zhang, 2021). Second, the National Air Quality Monitoring and Disclosure System implemented in 2013, aimed at establishing an effective system for monitoring air quality and disclosing data in real-time. Barwick et al. (2019) showed that this cost-effective policy can increase people's access to and understanding of pollution and its hazards, leading to more pronounced short-term and long-term avoidance behaviors, enhancing the effectiveness of environmental regulations and public demand for environmental regulation, and effectively controlling the impact of air pollution. To verify the robustness of the results, two additional estimations are performed. The first incorporates the low-carbon city pilot policy dummy variable into the control variables of the benchmark model. The second excludes data from 2014 to 2015 to mitigate the potential policy lag effect associated with air quality disclosure. The regression outcomes, presented in Table 4, Columns (3) and (4), indicate that after accounting for the low-carbon city pilot policy and removing the influence of air quality disclosure, both coefficients remain statistically significant at the 5% level. Furthermore, the results align with the benchmark findings in Table 3, reinforcing the robustness of the conclusions.

4.3.3 Placebo test

To further validate the robustness of the benchmark results, this study conducts a placebo test on the estimation outcomes. This approach helps mitigate potential biases in regression results arising from omitted variables and unobservable factors, thereby strengthening the credibility of the policy's treatment effect. The placebo test is implemented by randomly assigning a control group to determine whether the observed effects of cross-regional collaborative development on pollution and carbon reduction stem from random factors. Specifically, the designation of each city within the YREB is randomly reassigned. Figure 4 illustrates the coefficient distribution after 500 simulations, comparing the actual policy effect with the placebo results. The findings indicate that the distribution of P-values from the regression analysis and the kernel density of the regression coefficients are largely consistent with a normal distribution. The regression coefficients are centered around zero, with most showing no statistical significance. This suggests that the effectiveness of the cross-regional collaborative development policy in pollution reduction and carbon emission mitigation exhibits a degree of stability.

5 Mechanisms

This study explores the impact mechanism of cross-regional coordinated development policies through three key pathways: industrial green transition (structural), clean energy system transformation (technological), and low-carbon technology diffusion (knowledge-based). First, industrial green transition reduces the proportion of high-energy-consumption and high-emission industries through structural adjustments, aligning emission reduction with regional development needs and fostering the growth of green, low-carbon industries. This process ultimately leads to environmental improvements. Existing studies (Yu and Liu, 2020) indicate that industrial upgrading mitigates emissions by altering the structure of economic activities. This study

TABLE 3 Benchmark regression results.

Variables	(1)	(2)	(3)	(4)
	D	D	D	D
$Treat_c \times Post_y$	0.0391*	0.0368*	0.0520**	0.0468**
	(0.0204)	(0.0211)	(0.0219)	(0.0223)
GDPPC		0.00621		0.00499
		(0.00655)		(0.00659)
PD		−0.000241		−0.000265
		(0.000169)		(0.000168)
GC		0.00148		0.00155
		(0.00127)		(0.00126)
PRI		5.16e-05		7.50e-05
		(0.000261)		(0.000257)
SEC		−0.00467**		−0.00502**
		(0.00195)		(0.00195)
ST		1.698		1.809
		(2.541)		(2.520)
EDU		2.492*		2.509*
		(1.463)		(1.464)
UR		0.497**		0.485**
		(0.220)		(0.217)
ATP			4.60e-05	3.33e-05
			(2.96e-05)	(2.97e-05)
MAP			0.00563***	0.00525***
			(0.00187)	(0.00186)
MWS			0.00715	−0.00945
			(0.0410)	(0.0412)
MAT			−0.0428*	−0.0365
			(0.0230)	(0.0230)
MRH			0.00694	0.00812*
			(0.00432)	(0.00438)
Constant	1.089***	0.937***	−4.320***	−4.188**
	(0.00712)	(0.194)	(1.668)	(1.652)
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	1,446	1,443	1,446	1,443
R-squared	0.886	0.888	0.888	0.892

Notes: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. Standard errors, presented in parentheses, are clustered at the city-year level.

adopts the ratio of tertiary industry added value to secondary industry added value as an indicator of industrial structural adjustment, reflecting the extent of economic transition toward cleaner industries (Zhu et al., 2019). Based on this, cross-regional coordination policies not only contribute to emission reductions but also drive local governments and enterprises to proactively adjust

TABLE 4 Robustness test results.

Variables	(1)	(2)	(3)	(4)
	D	D	D	D
$Treat_c \times Post_y$	0.0302*	0.0286*	0.0477**	0.0477*
	(0.0169)	(0.0155)	(0.0231)	(0.0273)
GDPPC	0.00803	0.0104**	0.00620	−0.000830
	(0.00501)	(0.00457)	(0.00675)	(0.00736)
PD	−0.000215*	−0.000193*	−0.000274	−0.000317*
	(0.000127)	(0.000116)	(0.000170)	(0.000190)
GC	0.00164*	0.00163*	0.000238	−0.000292
	(0.000955)	(0.000872)	(0.00139)	(0.00176)
PRI	4.70e-05	3.02e-05	7.88e-05	4.94e-05
	(0.000195)	(0.000177)	(0.000261)	(0.000259)
SEC	−0.00545***	−0.00599***	−0.00510**	−0.00346*
	(0.00149)	(0.00137)	(0.00199)	(0.00209)
ST	0.356	0.163	1.646	0.321
	(1.915)	(1.748)	(2.591)	(2.881)
EDU	0.805	0.264	2.541*	2.456
	(1.113)	(1.042)	(1.514)	(1.648)
UR	0.407**	0.265*	0.443**	0.813***
	(0.165)	(0.153)	(0.220)	(0.283)
ATP	5.49e-05**	4.86e-05**	3.44e-05	4.01e-05
	(2.26e-05)	(2.07e-05)	(3.04e-05)	(3.03e-05)
MAP	0.00399***	0.00392***	0.00541***	0.00711***
	(0.00141)	(0.00129)	(0.00189)	(0.00197)
MWS	0.00712	0.0220	−0.00693	−0.0266
	(0.0313)	(0.0286)	(0.0420)	(0.0471)
MAT	−0.0216	−0.0199	−0.0355	−0.0764***
	(0.0175)	(0.0160)	(0.0236)	(0.0255)
MRH	0.00664**	0.00553*	0.00955**	0.00777
	(0.00333)	(0.00307)	(0.00449)	(0.00508)
Low-carbon city pilot policy			−0.0662**	
			(0.0312)	
Constant	−3.061**	−2.880**	−4.356***	−5.459***
	(1.256)	(1.150)	(1.681)	(1.710)
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	1,443	1,413	1,407	1,202
R-squared	0.926	0.929	0.891	0.907

Notes: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. Standard errors, presented in parentheses, are clustered at the city-year level.

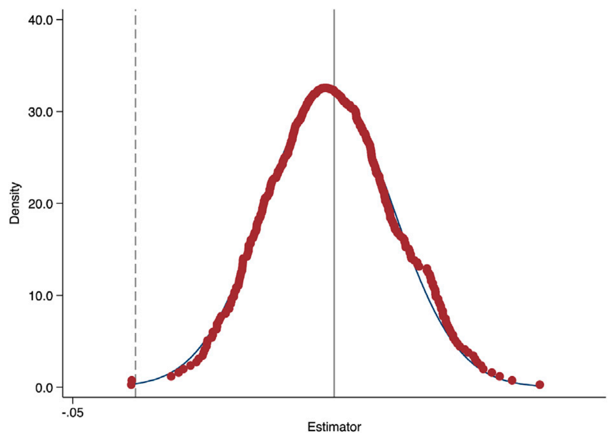

FIGURE 4
Placebo test.

industrial structures based on the inherent demands of regional economic upgrading, rather than merely complying with policy constraints to achieve environmental improvements. Second, the transition to a cleaner energy system supports long-term regional low-carbon development by leveraging energy technology innovations to reduce reliance on fossil fuels, thereby lowering pollutant and greenhouse gas emissions. However, due to data limitations, prefecture-level cities often lack continuous records of coal consumption rates or non-fossil energy adoption. To address this issue, this study employs *per capita* electricity consumption as a proxy variable to measure the degree of electrification and clean energy transition, reflecting the trend of electricity replacing coal (Lin and Li, 2020). When energy structure optimization is integrated with local industrial development and investment returns, regional governance is no longer solely dependent on policy mandates but becomes an endogenous requirement for industrial upgrading and energy market development. This enhances local governments' initiative in promoting low-carbon transitions, making the process more sustainable. Third, low-carbon technology diffusion facilitates the interregional spillover of green technologies, fostering a long-term governance mechanism driven by market adoption of green innovations. By following existing literature (Xiang and Geng, 2024), this study employs the proportion of green patents in total patents (tec) as an indicator of green technology development, reflecting the contribution of green innovation to pollution-carbon synergy governance. When the diffusion of low-carbon technologies shifts from being policy-driven to market-driven, enterprises, under competitive pressures and market incentives, actively adopt green technologies (Lin and Chen, 2022). Ultimately, this transition embeds low-carbon innovation into the regional economic development framework as an intrinsic driving force rather than a short-term policy intervention.

This study constructs a DID variable representing cross-regional cooperation policies and interacts it with the mechanism variables to examine whether the policy enhances pollution-carbon synergy through industrial upgrading (structural), energy transition (technological), and technology diffusion (knowledge-based). The empirical results, presented in Table 5, further validate the mechanism by which cross-regional policies drive coordinated governance of pollution and carbon reduction. As presented in Table 5, in models (1), (2), (3), and (4), where D is the dependent variable, the interaction terms did*iag, did*tec, and did*iag*es*tec exhibit statistically significant positive coefficients at the 1% level, while did*es is significantly positive at the 10% level. This indicates that industrial structure adjustment, the green transformation of the energy structure, and advancements in green technology contribute to strengthening the synergy between cross-regional pollution control and carbon reduction. Moreover, green technology progress, by utilizing geographical advantages to promote regional collaboration and shared innovation, can accelerate the adoption and implementation of green advancements. This, in turn, facilitates the achievement of cross-regional pollution mitigation and carbon reduction objectives. More importantly, the empirical results imply a fundamental transformation in environmental governance—from short-term, policy-driven interventions to a long-term, endogenous coordination mechanism driven by regional economic development needs. Specifically: First, industrial structural adjustments enable local governments and enterprises to naturally reduce the share of high-carbon-emission industries during economic upgrading, thereby decreasing reliance on policy interventions. Second, innovations in clean energy technologies drive energy transitions as a market-driven process rather than an administrative mandate. Third, the spillover of green technologies facilitates regional knowledge diffusion, encouraging enterprises and local governments to actively adopt green technologies, achieving long-term sustainable pollution-carbon synergy governance. This finding challenges the conventional paradigm of environmental governance that relies heavily on sector-specific policies. Instead, it provides a new explanatory framework, suggesting that cross-regional cooperation is not merely a policy instrument but a structural mechanism that fosters a long-term, institutionalized governance framework. Ultimately, environmental governance objectives no longer function as passive responses to policy pressures but emerge naturally from regional economic coordination, marking a shift from "policy-driven external enforcement" to "development-driven endogenous governance."

6 Conclusion

This study utilizes a coupling coordination model and DID model, employing panel data from 259 prefecture - level cities in China (2014–2019), to empirically evaluate the impact of cross - regional collaborative development policies, exemplified by the Outline of YREB, on pollution reduction and carbon emission mitigation. The results show that the policy has a significant synergistic effect, enhancing the coordination between pollution control and carbon mitigation across cities in the YREB. This effect is mainly driven by industrial restructuring, the green transformation of energy systems, and advancements in green technologies. These findings provide empirical evidence supporting the role of regional collaboration in strengthening environmental governance and offer valuable policy insights for other regions in China.

TABLE 5 Influencing mechanism analysis.

Variables	(1)	(2)	(3)	(4)
	D	D	D	D
did*iag	0.149*** (0.0197)			
did*es		0.00485* (0.00293)		
did*tec			0.774*** (0.183)	
did*iag*es*tec				0.212*** (0.0205)
Socioeconomic control variable	control	control	control	control
Meteorological control variable	control	control	control	control
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	1,202	1,378	1,443	1,145
R-squared	0.884	0.891	0.891	0.891

Notes: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. Standard errors, presented in parentheses, are clustered at the city-year level.

To improve regional collaborative governance, this study suggests the following policies. First, stronger cross-regional coordination and better policy alignment are needed. Setting common environmental standards, like shared pollution control targets, carbon pricing rules, and joint monitoring systems, can make policies more consistent and reduce differences between provinces. Regional emissions trading systems (ETS) and coordinated tax incentives can also help local governments work toward common sustainability goals. In addition, stronger environmental agreements and legal rules across regions can create a binding system for cooperation, ensuring stable policies and effective enforcement over time.

Second, speeding up the green transition in industry and energy is key. Governments should support industrial upgrades with clear green transition plans for each sector. They can offer financial help, like low-interest green loans, subsidies for clean technology, and tax breaks for businesses using low-carbon solutions. A regional green supply chain should be built to promote cleaner production and low-carbon transportation across cities. In the energy sector, improving regional power grid connections and clean energy trading can help distribute renewable energy more effectively, cutting reliance on fossil fuels. More investment in smart grids, energy storage, and local energy systems should also be a priority to improve efficiency.

Third, stricter environmental rules and better technology can make governance more effective. Real-time monitoring using big data, satellite sensing, and AI-powered pollution tracking can help detect problems early and enable policymakers to take swift action. Governments should also require companies to disclose environmental performance, encouraging greener production. More funding should go toward research on carbon capture, advanced emission reduction, and circular economy models to ensure technology plays a key role in sustainability.

Lastly, involving the public and working with other countries is important for better environmental governance. Digital campaigns, eco-education, and community-led projects can raise awareness and encourage people to take part in reducing pollution and carbon emissions. Governments should also empower local communities, businesses, and NGOs help shape and carry out policies. Stronger international cooperation through green finance, technology sharing, and global agreements—especially with Belt and Road Initiative (BRI) partners—can help China adopt the best global practices for regional sustainability. Moreover, while this study is grounded in the Chinese context, its findings hold broader relevance for other developing economies grappling with similar issues such as interregional disparities, environmental policy fragmentation, and the need for coordinated green transitions. The Yangtze River Economic Belt demonstrates how cross-regional collaboration—through pathways like industrial upgrading, cleaner energy adoption, and green technology diffusion—can effectively enhance the synergy between pollution control and carbon mitigation. These experiences may inform similar governance efforts in other contexts. For instance, India's attempts to align national and subnational environmental strategies, Southeast Asia's cooperation on transboundary air pollution, and Latin America's pursuit of regional sustainability frameworks all face coordination challenges that echo the Chinese case. Comparative research is encouraged to explore how such collaborative mechanisms might be tailored to diverse political and institutional conditions in other regions.

Despite its contributions, this study has several limitations. First, the heterogeneous effects of cross-regional policies across cities with different economic structures, environmental capacities, and governance conditions require further exploration to develop more tailored and effective policy measures. In particular, variations in local administrative capacity, political willingness, and institutional alignment may influence how regions respond to coordinated policies. While these political dimensions are not the central focus of this study, they represent important factors that merit further investigation. Second, while the study focuses on short-to medium-term impacts, the long-term evolution of regional collaboration, especially in response to technological advancements and shifts in global environmental governance, remains uncertain. Third, the analysis relies on panel data from 2014 to 2019, as the CEADs database currently lacks more recent city-level data. Although this temporal limitation restricts assessment of the latest policy effects, it offers a valuable historical perspective, allowing us to examine how past regional collaboration efforts have shaped governance strategies. Moreover, CEADs is widely recognized as the most authoritative source of city-level carbon emissions in China, particularly given the absence of unified local accounting standards. Its methodological rigor and alignment with domestic reporting practices further enhance the reliability and policy relevance of the findings. Future research could integrate updated datasets as they become available or leverage alternative sources, such as satellite-based environmental monitoring, to extend the temporal scope. Lastly, expanding comparative analyses beyond the Yangtze River Economic Belt to other regions and international contexts would allow for a deeper examination of how coordination mechanisms perform under different institutional, political, and ecological contexts.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

ZY: Conceptualization, Writing – original draft, Writing – review and editing. ZZ: Writing – review and editing, Funding acquisition, Supervision. SZ: Writing – original draft, Methodology. AQ: Funding acquisition, Resources, Writing – review and editing.

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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.

Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript. Revised parts of the manuscript for language clarity.

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