

Article

Synergistic Governance of Pollution Reduction and Carbon Mitigation Through Air Quality Ecological Compensation: Evidence from China

Zhuo Chen  and Qingxuan Bu * 

Management and Economics College, North China University of Water Resources and Electric Power, No. 136 Jinshui East Road, Zhengdong New District, Zhengzhou 450011, China; chenzhuo@ncwu.edu.cn

* Correspondence: bq15936862262@gmail.com; Tel.: +86-15936862262

Abstract

Atmospheric pollutants and CO₂ share common origins in fossil fuel combustion, raising the question of whether fiscal incentives targeting air quality alone can indirectly reduce carbon emissions. This study examines this question by evaluating China's air quality ecological compensation policy, a provincial-level horizontal fiscal transfer mechanism under which cities are rewarded or penalized according to changes in ambient air quality indicators, without incorporating any explicit carbon-related assessment criteria. Using panel data from 268 prefecture-level cities over 2007–2023 and a multi-period difference-in-differences design, we find that the policy significantly reduces the composite pollution carbon index ($\beta = -0.213, p < 0.01$), with the effect confirmed by an alternative weighted-average specification ($\beta = -0.153, p < 0.01$) and robust to propensity score matching, one-period lagged regression, exclusion of provincial-level municipalities, and exclusion of the COVID-19 period. A two-step mechanism analysis, adopted to avoid post-treatment bias from “bad controls,” reveals that the policy promotes industrial structure upgrading ($\beta = 0.253, p < 0.01$), enhances green technological innovation capacity ($\beta = 0.047, p < 0.10$), and reduces energy consumption intensity ($\beta = -0.012, p < 0.01$). Heterogeneity analysis based on quartile subsamples shows that the synergistic benefits concentrate in cities with stronger fiscal capacity ($\beta = -0.349, p < 0.01$ versus insignificant for low-support cities), higher economic development, and greater urbanization ($\beta = -1.558, p < 0.01$ for highly urbanized cities), while the policy effect is statistically insignificant in the least-advantaged subgroups across these three dimensions. In contrast, the green coverage dimension reveals an opposite pattern: the effect is strongest in cities with lower green coverage ($\beta = -0.378, p < 0.05$) and insignificant in high-coverage cities, indicating diminishing marginal returns where environmental baselines are already favorable. These findings highlight the need for differentiated compensation standards, including tiered compensation coefficients and targeted fiscal support for resource-constrained regions, to ensure equitable governance outcomes.



Academic Editor: Giouli Mihalakakou

Received: 15 March 2026

Revised: 31 March 2026

Accepted: 13 April 2026

Published: 15 April 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: air quality ecological compensation; synergistic governance; carbon co-benefits; indirect fiscal incentives; multi-period DID; mechanism analysis; heterogeneity analysis; differentiated compensation standards

1. Introduction

Climate change and air pollution are closely intertwined because both are strongly associated with fossil-fuel-based production and energy use. Fossil fuel combustion,

the dominant source of anthropogenic CO_2 , also releases SO_2 , NO_x , and primary fine particulate matter, a pattern widely observed in industrialized cities (Figure 1) [1,2]. After emission, these pollutants may undergo further atmospheric transformation: SO_2 forms sulfate aerosols, NO_x reacts with NH_3 to form nitrate and ammonium aerosols, VOCs oxidize into secondary organic aerosols, and NO_x combines with VOCs under sunlight to generate ground-level ozone (Figure 2). These shared sources and transformation pathways imply that pollution-control policies may also generate carbon-mitigation co-benefits, a proposition increasingly emphasized in the sustainable development literature [3,4].



Figure 1. Industrial pollution in Chinese cities.

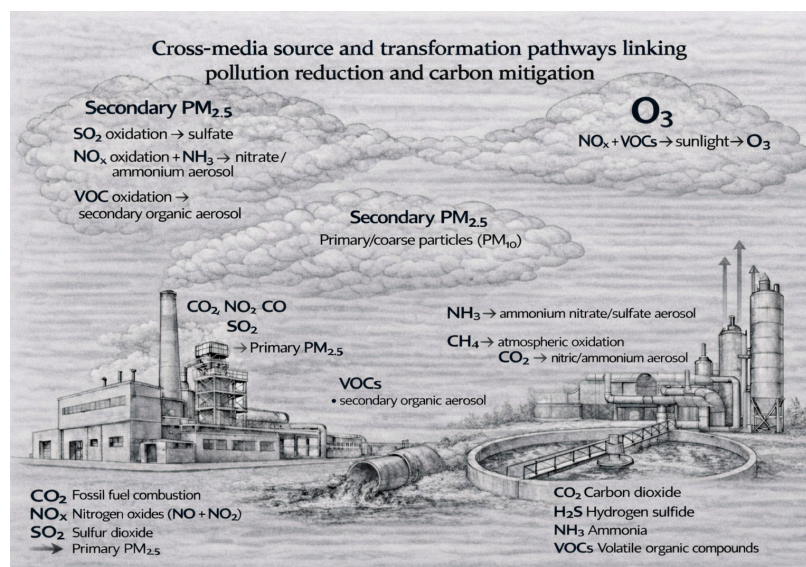


Figure 2. Cross-media pollution-carbon pathways.

The urgency of exploiting such synergies is underscored by the severity of both crises: 2024 was confirmed as the hottest year on record, with global average temperatures exceeding the Paris Agreement's 1.5°C threshold for the first time, while air pollution has surpassed hypertension and smoking to become the leading global disease risk factor [5,6]. For China—the world's largest carbon emitter and a country where warming from 1.5°C to 2°C would cause over 27,900 additional annual heat-related deaths—achieving synergistic pollution reduction and carbon mitigation is not merely desirable but imperative [7].

In response to this dual imperative, China has over the past decade deployed a suite of regulatory and market-based instruments targeting both dimensions.

China's governance response unfolded along two parallel tracks. On the air quality side, the Action Plan for Air Pollution Prevention and Control (commonly known as the "Ten Measures for the Atmosphere," 2013–2017) imposed stringent emission reduction targets across key regions and sectors, followed by the Three-Year Action Plan for Winning the Blue Sky Defense War (2018–2020) that extended and deepened these measures. Empirical evidence confirms the effectiveness of these interventions: China's two-phase clean air actions reduced national population-weighted average PM_{2.5} concentrations by 19.8 µg/m³ during 2013–2017 and by a further 10.9 µg/m³ during 2018–2020 [8], while the Three-Year Action Plan additionally promoted high-quality regional energy development, partly through stimulating technological innovation [9]. On the carbon side, carbon emissions trading pilots were launched in seven provinces and cities beginning in 2013 and subsequently consolidated into a national carbon market in 2021. Evidence from these pilots suggests that market-based emissions reduction mechanisms can foster high-quality economic development alongside green transition, though short-term economic volatility may arise during the adjustment period [10,11]. Meanwhile, three batches of low-carbon city pilots were designated in 2010, 2012, and 2017, respectively, to explore pathways for decoupling economic growth from carbon emissions; assessments indicate that such policies have effectively reduced aggregate carbon emissions in pilot cities while progressively improving their dynamic carbon emission efficiency [12].

Whether these instruments—and analogous policies elsewhere—can deliver genuine co-benefits by simultaneously reducing air pollutants and carbon emissions has become a central question in environmental governance research. A substantial body of literature has investigated the foundations and empirical manifestations of such synergies across multiple dimensions. Spatiotemporal analyses across over 13,000 urban areas reveal significant positive correlations between atmospheric pollutant and greenhouse gas concentrations, confirming shared emission origins as a near-universal phenomenon [13]. At the intervention level, diverse policy instruments—including carbon pricing [14], emissions trading [15], and stringent environmental regulation—have been shown to deliver simultaneous reductions in both pollutants and carbon [16], while sector-specific studies demonstrate that steel industry emission reduction technologies in provinces overlapping with China's air quality ecological compensation pilots can achieve substantial synergistic effects, some at negative marginal abatement costs, suggesting that not all pollution control technologies entail a carbon penalty [17]. At the outcome level, the co-benefits are economically significant: health gains from China's carbon peaking pathway could substantially offset mitigation costs [18], and globally, air quality improvements from meeting Paris Agreement pledges can counterbalance climate policy expenditures [19]. Taken together, these findings have established a broad consensus that synergistic governance is scientifically grounded, technically feasible, and economically rational. Yet this consensus has been built predominantly around policies that directly target carbon emissions or simultaneously regulate multiple pollutants. Carbon pricing, emissions trading, and comprehensive environmental standards create explicit incentives for both pollution and carbon reduction by design. A fundamentally different—and largely unexamined—question is whether policies designed exclusively around air quality metrics can generate carbon mitigation as an indirect co-benefit through the behavioral and structural adjustments they induce. This distinction is theoretically consequential: it tests whether the "common root and source" linkage is sufficiently strong that fiscal incentives tied solely to pollutant concentrations can propagate through economic systems to produce measurable carbon reductions, even absent explicit carbon-related policy targets.

China's air quality ecological compensation policy provides a suitable institutional setting for examining this issue. Initiated in Shandong and Hebei in 2014 and later extended to other provinces, the policy establishes a provincial-level horizontal fiscal transfer system under which cities with worsening air quality make compensation payments, whereas cities with improving air quality receive fiscal rewards. In most provinces, the assessment is based on changes in PM_{2.5}, PM₁₀, SO₂, and NO₂ concentrations, while some provinces additionally include O₃ or CO in light of local pollution conditions [20]. Critically, the policy contains no explicit carbon-related assessment criteria and therefore operates primarily as an air-pollution governance instrument. A growing literature has evaluated its environmental effects along three dimensions. Regarding direct air quality impacts, the policy significantly reduces PM_{2.5} concentrations, with effects concentrated in economically developed regions and cities facing lower fiscal pressure [21]; Chang et al. (2024) add important nuance, showing that the policy primarily benefits non-compliant cities but that the absence of penalty mechanisms induces strategic prioritization of low-cost pollutants [22]. Regarding behavioral and efficiency channels, the policy enhances total factor energy efficiency through industrial restructuring and green innovation and increases corporate pollution control investment, particularly in state-owned enterprises and heavily polluting sectors [23,24]. Regarding policy complementarities and welfare outcomes, synergies with pollution taxes strengthen emission reductions by compensating for market failures [25], and the policy improves environmental welfare performance, with stronger effects in service-oriented, non-resource-based cities [26]. These studies have substantially advanced understanding of how the policy works and for whom. However, all existing evaluations adopt single-objective frameworks, assessing impacts on air pollution, energy efficiency, or enterprise behavior in isolation. None has systematically examined whether the pollution reduction achieved through this policy is accompanied by—and mechanistically linked to—carbon mitigation outcomes. Given that the policy provides only air-quality-based fiscal incentives, whether the structural, technological, and efficiency adjustments it induces are sufficient to generate measurable carbon co-benefits cannot be assumed from the broader co-benefits literature and requires dedicated empirical investigation.

This gap carries practical significance as China commits to carbon peaking before 2030. Air quality ecological compensation has expanded to cover numerous provinces since its 2014 pilot, establishing extensive institutional infrastructure. If this infrastructure can demonstrably deliver carbon co-benefits, it would reframe the policy from a single-purpose air quality tool into a dual-purpose instrument for both pollution and climate governance, with important implications for cost-effective policy portfolio design. We construct a composite pollution carbon emissions index to jointly capture synergistic governance performance and examine three theoretically motivated transmission channels: advanced industrial structure, green technological innovation, and energy consumption intensity. Our analysis contributes to the literature in three respects. First, by evaluating pollution and carbon outcomes within a unified empirical framework, we extend the evidence base on air quality ecological compensation beyond single-objective assessments. More broadly, we contribute to the co-benefits literature by testing whether indirect fiscal incentives—those not explicitly targeting carbon—can generate meaningful carbon mitigation through the behavioral adjustments they induce, thereby probing the empirical boundaries of the “common root and source” proposition. Second, rather than invoking established theories in isolation, we examine how a single fiscal incentive mechanism simultaneously activates multiple transmission channels—structural adjustment through externality internalization [27], technological change through Porter-type innovation offsets [28], and efficiency improvement through induced factor-saving responses [29,30]. This integrated perspective reveals the complementary nature of these pathways and the conditions under which

fiscal incentives translate into multi-dimensional environmental improvements. Third, our heterogeneity analysis documents that the policy's synergistic benefits are concentrated in cities with strong fiscal capacity, high economic development, and advanced urbanization, while the green coverage dimension reveals a contrasting pattern where cities with worse environmental baselines benefit most—raising important equity concerns and providing evidence-based justification for differentiated compensation standards and targeted support for resource-constrained regions.

The remainder of this paper is organized as follows. Section 2 develops the theoretical framework and research hypotheses. Section 3 describes the research design, including data, model specification, and variables. Section 4 presents the empirical results. Section 5 conducts heterogeneity analysis. Section 6 concludes with policy recommendations.

2. Theory and Hypotheses

2.1. Air Quality Ecological Compensation Policy

As established in the Introduction, the co-benefits literature has demonstrated that policies directly targeting carbon emissions, such as carbon pricing and emissions trading, can simultaneously reduce air pollutants. Air quality ecological compensation operates through a fundamentally different incentive logic. The policy establishes horizontal fiscal transfers among prefecture-level cities coordinated by provincial governments, creating a “polluter pays, beneficiary compensates” mechanism based on changes in ambient air quality indicators [20]. Cities with deteriorating air quality face fiscal penalties, whereas those achieving improvements receive fiscal rewards linked to observed changes in pollutant concentrations.

Traditional environmental policy instruments, whether command-and-control or market-based, each face well-documented limitations. Command-and-control instruments lack flexibility and cost efficiency, while market-based instruments exhibit limited effectiveness under information asymmetry and market failure [31]. Air quality ecological compensation represents a hybrid design that maintains rigid constraints through mandatory fiscal rewards and penalties while granting local governments flexibility in selecting governance pathways and allocating resources. Theoretically, this design draws on two complementary frameworks. Pigou's externality correction theory explains how the policy internalizes transboundary pollution costs: by establishing conditional horizontal transfer payments [27], the policy transforms external environmental damage into direct fiscal consequences for local governments, aligning private and social costs. Fiscal federalism theory further explains how such horizontal fiscal transfers alter local incentive structures [32,33], guiding government behavior toward socially optimal outcomes and prompting the search for new equilibria between economic development and environmental protection.

The critical question is whether these pollution-oriented fiscal pressures also translate into carbon mitigation. There are theoretical grounds for expecting such an effect. Because the policy targets pollution outcomes that are closely associated with fossil-fuel-intensive production and energy use, governance measures that reduce emissions at the source, such as restricting coal consumption, eliminating inefficient capacity, and promoting cleaner production, may also reduce CO₂ emissions (see Figure 2). Under reward-and-penalty incentives, local governments are likely to strengthen energy-conservation supervision, support cleaner technologies, and promote industrial restructuring, all of which may contribute to carbon mitigation while improving air quality.

However, this synergistic outcome is far from guaranteed, and several countervailing forces may attenuate or even reverse the expected carbon co-benefits. First, the policy's exclusive focus on air pollutant concentrations creates incentives for local governments to prioritize the most cost-effective pollutant reduction strategies, which may not align with

carbon-optimal pathways. End-of-pipe treatment technologies, such as flue gas desulfurization and selective catalytic reduction, can effectively reduce SO_2 and NO_x concentrations but may require substantial energy inputs, potentially increasing carbon emissions per unit of pollutant removed [34]. That said, the carbon penalty varies by technology: certain steel-sector pollution control measures in the Beijing–Tianjin–Hebei region achieve simultaneous pollution and carbon reductions at negative marginal abatement costs [17]. The net carbon effect therefore depends not on whether end-of-pipe measures are adopted, but on the specific technology mix local governments assemble in response to fiscal incentives. Second, the absence of carbon-related assessment criteria means that local governments face no fiscal penalty for adopting pollution control strategies that are carbon-intensive, creating a potential wedge between air quality improvement and carbon mitigation. A further concern is the policy’s quarterly assessment cycle. Short-term performance pressure could, in principle, bias local governments toward end-of-pipe installations that deliver rapid pollutant concentration reductions at the expense of longer-gestation source-reduction strategies. Three features of the policy’s design constrain this tendency. First, compensation amounts are calibrated to concentration changes, so one-time end-of-pipe installations yield diminishing fiscal returns across successive quarters, whereas sustained source-reduction measures generate cumulative rewards. Second, the quarterly cycle is embedded within provincial governance frameworks that impose annual and multi-year environmental targets, encouraging a balance between short-term compliance and medium-term structural adjustment. Third, simultaneous assessment of four pollutants ($\text{PM}_{2.5}$, PM_{10} , SO_2 , and NO_2) makes systemic source-reduction measures more cost-effective than pollutant-by-pollutant end-of-pipe solutions. Nonetheless, the quarterly rhythm likely encourages a mixed response in which end-of-pipe measures provide immediate relief while source-reduction investments gradually mature, with the net carbon outcome depending on the evolving balance between these two response types. Third, if the fiscal incentive is insufficient to induce fundamental structural change and instead triggers only incremental, low-cost adjustments, such as relocating polluting enterprises to non-assessed jurisdictions rather than transforming them, carbon reductions may be negligible or geographically displaced rather than genuinely achieved. Whether the “common root and source” linkage produces a net positive effect is therefore an empirical question whose answer depends on the composition of local governments’ governance portfolios—specifically, the relative weight of source-reduction versus end-of-pipe responses—the depth of structural adjustment the policy induces, and the strength of the fiscal incentive relative to the cost of transformation.

We expect that local governments respond through a combination of source-reduction and end-of-pipe strategies. We hypothesize that the aggregate carbon co-benefits from the former—industrial restructuring, energy efficiency improvement, and cleaner technology adoption—outweigh the potential carbon costs of the latter, yielding a net positive synergistic effect:

Hypothesis 1. *Air quality ecological compensation policy significantly enhances cities’ synergistic governance of pollution reduction and carbon mitigation.*

2.2. Mechanism of Action

2.2.1. Advanced Industrial Structure

The reward-and-penalty mechanism fundamentally alters local governments’ industrial development preferences. Under the traditional “GDP tournament” model, local governments often prioritize developing high-pollution, high-carbon heavy and chemical industries for short-term economic growth. While structural transformation theory suggests that industrial structure tends to evolve from lower to higher stages as economies

develop [35,36], market failures and distorted governmental incentives frequently impede this process. Air quality ecological compensation corrects these distortions through externality internalization: by making air quality deterioration fiscally costly, the policy alters the relative cost benefit calculus of different industries, accelerating the reallocation of economic activity from pollution-intensive sectors toward cleaner, higher-value-added alternatives.

The expected synergistic effect of industrial upgrading operates primarily through reducing the share of energy-intensive industries that simultaneously emit both atmospheric pollutants and CO₂. Empirical evidence supports this dual impact: industrial restructuring significantly reduces PM_{2.5} concentrations and carbon emissions alike [37], as confirmed by both interprovincial panel analyses and regional studies [38,39].

This channel, however, is subject to important qualifications. The expansion of the tertiary sector does not uniformly reduce emissions; certain service industries, including transportation, logistics, and commercial real estate, are themselves energy-intensive. Moreover, structural transformation is an inherently gradual process whose pace may not align with the policy's quarterly assessment cycle. This temporal mismatch may lead local governments to supplement structural adjustment with end-of-pipe measures that provide immediate pollutant reductions during the transition period, partially attenuating the net carbon co-benefits of this channel. If the fiscal incentive is insufficient to overcome the adjustment costs of structural change, or if local governments respond by superficially reclassifying industries rather than genuinely transforming them, the carbon co-benefits may be modest. We therefore test the following hypothesis while remaining attentive to the possibility that the observed structural effects may be small relative to the scale of the challenge:

Hypothesis 2. *Air quality ecological compensation policy promotes synergistic governance of pollution reduction and carbon mitigation by facilitating advanced industrial structure.*

2.2.2. Green Technological Innovation Capacity

The Porter hypothesis and induced technological change theory provide complementary explanations for how environmental regulation stimulates innovation. The Porter hypothesis argues that well-designed regulation can induce innovation that offsets compliance costs through “innovation compensation effects”; induced technological change theory explains how factor price changes redirect innovative effort toward factor-saving technologies. Air quality ecological compensation, as a hybrid “carrot and stick” instrument, engages both mechanisms: it raises costs for high-pollution enterprises while reducing clean technology innovation costs through fiscal subsidies and R&D assistance, inducing cleaner production technology adoption [40,41].

The synergistic implications of green innovation, however, depend critically on the type of innovation induced. Source-reduction technologies, which prevent pollutant and carbon generation at the point of production, yield unambiguously positive co-benefits by simultaneously reducing fossil fuel inputs and their associated emissions. End-of-pipe treatment technologies, by contrast, remove pollutants from waste streams but may entail additional energy inputs, with carbon implications that vary by technology type—ranging from net carbon increases for energy-intensive scrubbing systems to net carbon decreases for integrated process improvements [21,34]. Empirical evidence on the aggregate effect is encouraging: green innovation significantly reduces both PM_{2.5} concentrations and carbon emissions with spatial spillover effects [42,43], indicating that the net carbon co-benefits of green innovation are positive when both technology types are considered jointly. Furthermore, the fiscal structure of ecological compensation, which rewards sustained air quality improvement rather than one-time compliance, is more likely to incentivize

fundamental process innovations over incremental end-of-pipe solutions, as only the former generate durable reductions in assessed pollutant concentrations.

Nevertheless, two additional concerns warrant acknowledgment. First, the “strong” version of the Porter hypothesis, that regulation-induced innovation fully offsets compliance costs, remains empirically contested, and the innovation response may be insufficient to generate net positive outcomes in all contexts. Second, rebound effects may partially erode efficiency gains if improved technologies lower production costs and thereby stimulate output expansion. We hypothesize that these countervailing forces are second-order relative to the direct emission reduction benefits of green innovation:

Hypothesis 3. *Air quality ecological compensation policy promotes synergistic governance of pollution reduction and carbon mitigation by enhancing green technological innovation capacity.*

2.2.3. Energy Consumption Intensity

Energy consumption intensity, defined as energy input per unit of GDP, provides a direct link between economic activity and environmental impact. The Kaya identity decomposes carbon emissions into population [44], per capita output, energy intensity, and carbon coefficients, identifying energy intensity as a key policy-amenable factor [45]. Air quality ecological compensation incentivizes local governments to prioritize energy efficiency through fiscal mechanisms: the threat of fiscal penalties for air quality deterioration prompts strengthened supervision of high-energy-consuming enterprises, promotion of energy-saving technological transformation, and acceleration of clean energy substitution. Evidence confirms that environmental policies can significantly enhance total factor energy efficiency and reduce urban energy consumption intensity [46,47].

Because fossil fuels constitute over 80% of China’s primary energy consumption during the study period, reducing energy intensity per unit of GDP simultaneously decreases atmospheric pollutants and CO₂ at the source. Research confirms that energy intensity significantly influences PM_{2.5} concentrations and correlates positively with carbon emission intensity [48,49], establishing it as a core pathway for synergistic governance.

This channel nonetheless faces a potential limitation. Energy intensity reductions may reflect both technical efficiency gains and the substitution of fossil fuels with cleaner energy sources, and both components may be partially offset by the rebound effect: as energy costs per unit of output decline, enterprises may expand production, eroding a portion of the initial energy savings. However, unlike end-of-pipe treatment, reducing energy consumption per unit of output is inherently source-reducing in nature. It decreases the total volume of fossil fuel combustion per unit of output, generating simultaneous reductions in both atmospheric pollutants and CO₂ without introducing additional energy-consuming processes. Combined with the fiscal penalty for air quality deterioration, which constrains the scale of emission-intensive production expansion, the net effect on synergistic governance is expected to be positive:

Hypothesis 4. *Air quality ecological compensation policy promotes synergistic governance of pollution reduction and carbon mitigation by reducing energy consumption intensity.*

3. Research Design

3.1. Data Sources

Given that cities are the basic units of human activities and the primary consumers of energy and emitters of carbon dioxide worldwide [50], this study investigates whether air quality ecological compensation policy truly and effectively promotes the synergistic achievement of the dual objectives of “pollution reduction” and “carbon mitigation”. To this

end, the study collects panel data from 268 prefecture-level and above cities in China from 2007 to 2023 (due to data availability) as the research sample. Data on the implementation of air quality ecological compensation policy are primarily compiled from air quality ecological compensation measures published on the websites of provincial (municipal, district) people's governments. Data required for calculating carbon emissions are sourced from the China City Statistical Yearbook, China Statistical Yearbook, and China Urban Construction Statistical Yearbook. Total wastewater discharge, sulfur dioxide emissions, and smoke and dust emissions data are all derived from the China City Statistical Yearbook. Green patent applications are obtained from the "green invention patent applications" in the National Intellectual Property Database. Other variables are sourced from the China City Statistical Yearbook and municipal national economic and social development statistical bulletins.

3.2. Model Specification

Based on existing literature, empirical studies commonly employ difference-in-differences (DID), synthetic control [51], and regression discontinuity design to evaluate environmental governance policies [52]. The DID method identifies the net policy effect by comparing changes in outcome variables between treatment and control groups before and after intervention, effectively controlling for time-invariant and individual heterogeneity [53]. This study employs a multi-period difference-in-differences framework as a quasi-natural experiment. Because the air quality ecological compensation policy was introduced in different provinces in different years, treatment status varies across cities and over time according to the timing of provincial policy adoption. Using panel data for 268 prefecture-level and above cities from 2007 to 2023, we estimate the following model:

$$SYOP_{it} = \beta_0 + \beta_1 DID_{it} + \gamma' Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

where i and t correspond to city and time, respectively; $SYOP_{it}$, the explained variable, refers to the logarithmic value of the pollution reduction and carbon mitigation level; The interaction term DID_{it} is the key explanatory variable, reflecting whether province i implemented air quality ecological compensation policy at time t ; $Control_{it}$ represents a column vector composed of six control variables, specifically population size, economic development level, foreign direct investment, financial development level, urbanization level, and government support. μ_i represents province fixed effects, λ_t represents year fixed effects, and ε_{it} is the random error term. All variables in the baseline model are indexed by city i and year t . For simplicity, subscripts are omitted in the main text and tables.

To further explore the action mechanisms of air quality ecological compensation policy on synergistic governance of pollution reduction and carbon mitigation, this study, based on theoretical analysis, investigates its mechanisms from three aspects: advanced industrial structure (Ais), green technological innovation capacity ($Gpatent$), and energy consumption intensity (EI). To avoid post-treatment bias caused by "bad control variables" resulting from incorporating mechanism variables alongside the treatment variable DID_{it} in the regression model [54], we adopt a "two-step approach". First, we identify the total effect of $D \rightarrow Y$. Then, we identify the mechanism response of $D \rightarrow M$.

This empirical strategy aims to examine whether the air quality ecological compensation policy significantly affects the proposed mediating channels that are theoretically and empirically associated with the outcome variable [55]. Given that the relationships between these mediating variables and pollution-carbon synergy outcomes (i.e., the $M \rightarrow Y$ linkage) have been extensively supported in prior literature, the analysis in this study focuses on testing whether the policy effectively induces changes in Ais , $Gpatent$, and EI ,

thereby providing evidence on the potential pathways through which the policy operates. The following model is thus constructed:

$$\begin{cases} SYOP_{it} = \beta_0 + \beta_1 DID_{it} + \gamma' Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \\ Mech_{it} = \alpha_0 + \alpha_1 DID_{it} + \Gamma' Control_{it} + \mu_i + \lambda_t + E_{it} \end{cases} \quad (2)$$

where $Mech_{it}$ represents mechanism variables, including advanced industrial structure (Ais_{it}), green technological innovation capacity ($Gpatent_{it}$), and energy consumption intensity (El_{it}); γ and Γ represent column vectors composed of regression coefficients corresponding to each control variable.

3.3. Variable Description

3.3.1. Explained Variable

The explained variable is the synergistic pollution reduction and carbon mitigation level ($SYOP$). This study uses three representative pollution indicators—total wastewater discharge, SO_2 emissions, and smoke and dust emissions—to construct the environmental pollution index [56]. The purpose is not to mechanically reproduce the policy's assessment formula, but to examine whether an air-quality-oriented fiscal incentive can generate broader environmental improvements together with carbon-mitigation co-benefits at the city level. This choice is appropriate for two reasons. First, local environmental governance measures are often systemic rather than medium-specific. Policies such as shutting down heavily polluting enterprises, adjusting industrial structure, and strengthening energy conservation can simultaneously affect water pollution, gaseous emissions, particulate emissions, and carbon emissions. Consistent with the cross-media pathways illustrated in Figure 2, limiting the outcome measure to a single ambient concentration indicator may understate the broader environmental consequences of the policy. Second, city-level data on some ambient concentration indicators are not consistently available over the full sample period, whereas total wastewater discharge, SO_2 emissions, and smoke and dust emissions provide a longer and more comparable panel [56]. On this basis, the selected indicators capture pollution across water, gaseous, and particulate dimensions and are used to evaluate whether the policy produces multi-media pollution reduction together with carbon mitigation.

The environmental pollution index (PE) of each city is constructed using an improved entropy weight TOPSIS method, which characterizes local ecological environment quality and environmental pollution degree [57]. The total carbon emissions (CE) of each city are calculated based on emission factor coefficients [58]. Given the common source characteristics of environmental pollutants and carbon emissions, the logarithmic value of the interaction term between PE and CE is used to measure the synergistic pollution reduction and carbon mitigation level ($SYOP$) [59]. Higher values of $SYOP$ indicate worse environmental quality, while lower values indicate better environmental performance. To further ensure that the results are not driven by potential mechanical correlation, this study constructs an alternative composite index ($SYOP-W$) as a robustness check. Specifically, $SYOP-W$ is obtained by taking the weighted average of carbon emissions and pollution emissions data and then standardizing the resulting index. Results based on $SYOP-W$ are reported as a robustness test.

3.3.2. Core Explanatory Variable

The core explanatory variable is whether air quality ecological compensation policy is implemented at the province level (DID), which takes values of 0 or 1. Specifically, if the province where the city is located implemented air quality ecological compensation policy in that year, DID takes the value of 1, otherwise 0. This variable is used to identify the

treatment effect of different provinces before and after policy implementation and serves as the key interaction term in the Multi-period DID model. The policy has been gradually rolled out since 2014. The construction of this variable reflects whether local governments are within this institutional incentive framework, thereby affecting their pollution control and carbon mitigation behaviors.

3.3.3. Mechanism Variables

Advanced industrial structure (*Ais*): Measured by the ratio of tertiary industry value-added to secondary industry value-added [60]. Larger values indicate a more advanced industrial structure with greater dominance of the service sector relative to manufacturing. This indicator captures the degree of economic structural advancement and the shift from resource-intensive secondary industry toward knowledge- and service-intensive tertiary industry. According to the Petty Clark theorem, industrial structure gradually transforms from primary industry dominance toward secondary and tertiary industry dominance as the economy develops, significantly impacting energy intensity and environmental quality, making it a crucial pathway for pollution reduction and carbon mitigation.

Green technological innovation capacity (*Gpatent*): Measured by the natural logarithm of the total number of green invention patent applications. Compared with other types of green patents, green invention patents involve higher technological content and stricter examination standards, and thus better capture substantive green innovation and its quality dimension. Accordingly, recent studies tend to use green invention patent applications as a proxy for green innovation capacity [61]. Green invention patents mainly cover environmental protection, clean energy, and energy conservation technologies, and thus comprehensively reflect urban green innovation activity and capability. Through technological progress in source reduction and end-of-pipe treatment, green innovation can effectively reduce pollutant emissions and carbon intensity per unit of output, serving as a key driving force for pollution reduction and carbon mitigation.

Energy consumption intensity (*EI*): Measured by energy consumption per unit GDP, the ratio of total energy consumption to regional GDP. This indicator reflects economic systems' energy dependence and utilization efficiency, encompassing energy input output relationships across production and consumption. As a characterization of economic development quality, energy intensity directly relates to energy consumption and carbon emission levels per unit output, constituting a core indicator for assessing synergistic pollution reduction and carbon mitigation effects.

3.3.4. Control Variables

Following existing literature [62,63], this study selects six control variables: Population size (*POP*), measured by the natural logarithm of year-end resident population, controls for population scale effects on pollution and technology diffusion; Economic development level (*GDP*), expressed by the natural logarithm of regional GDP, reflects regional economic development; Financial development level (*FIN*), measured by the ratio of total financial institution deposits and loans to GDP, captures financial support for green innovation and industrial transformation; Foreign direct investment (*FDI*), measured as the ratio of FDI to GDP, reflects regional openness and potential environmental impacts of foreign capital; Urbanization level (*UR*), expressed by the urban population proportion, depicts urbanization's impact on energy consumption structure and spatial layout; Government support (*GOV*), measured by the ratio of local fiscal expenditure to GDP, indicates fiscal capacity determining environmental governance resource input.

Descriptive statistics are presented in Table A1.

4. Results and Discussion

4.1. Benchmark Regression

Table A2 reports the benchmark regression results. To provide a more granular understanding of the policy's effects, we first examine its impact on the two components of the composite index separately: column (1) reports the regression with the pollution emission index (*PE*) as the dependent variable, and column (2) reports the regression with carbon emissions (*CE*) as the dependent variable. Column (3) presents the main specification using the composite synergistic index (*SYOP*). Column (4) reports a robustness check using the weighted-average composite index (*SYOP-W*), which replaces the logarithmic product with a standardized additive specification to rule out mechanical correlation from shared fossil fuel sources. All specifications include the full set of control variables and province and year fixed effects.

In column (1), the *DID* coefficient on *PE* is -0.029 (1% level), indicating that the policy significantly reduces the environmental pollution index. In column (2), the *DID* coefficient on *CE* is -0.017 (1% level), confirming that the policy also significantly reduces carbon emissions despite containing no carbon-related assessment criteria. Column (3) presents the composite *SYOP* results: the *DID* coefficient is -0.213 (1% level), indicating that air quality ecological compensation policy significantly reduces the integrated level of urban pollution and carbon emissions, effectively promoting synergistic governance of pollution reduction and carbon mitigation, validating Hypothesis 1. Column (4) confirms the robustness of this finding: when the dependent variable is replaced with *SYOP-W*, the *DID* coefficient remains significantly negative at -0.153 (1% level), demonstrating that the synergistic effect is not an artifact of the multiplicative index construction and survives an alternative additive specification.

Regarding control variables, the results align with expectations: population size (*POP*) coefficients are significantly positive across all specifications, indicating that population expansion increases pollution and carbon emission pressure; foreign direct investment (*FDI*) is significantly negative in the *SYOP* and *SYOP-W* specifications, suggesting technology spillover effects improve environmental quality; urbanization level (*UR*) is significantly positive, reflecting resource consumption pressure during urbanization; government support (*GOV*) is significantly negative in the *SYOP* specification, indicating fiscal expenditure contributes to environmental governance.

4.2. Parallel Trends Test

To ensure the validity of the multi-period difference-in-differences model, we conduct an event study analysis that accounts for the staggered provincial rollout of the policy. We construct a relative time indicator for each city, defined as the difference between the calendar year and the city's own policy implementation year, and estimate dynamic coefficients for each relative period from $t - 5$ to $t + 5$ with $t - 1$ as the baseline. Figure 3 reports the results. The horizontal axis represents relative time to each city's individual treatment year, ensuring that cities entering the policy in different years are aligned at their respective treatment dates. As observed from the figure, before policy implementation, the estimated coefficients for each relative period fluctuate slightly around zero. The 95% confidence intervals all include zero, and the coefficients are not statistically significant. This indicates that the treatment and control groups exhibited fundamentally consistent development trends before policy implementation, with no significant systematic differences, thus satisfying the parallel trends assumption.

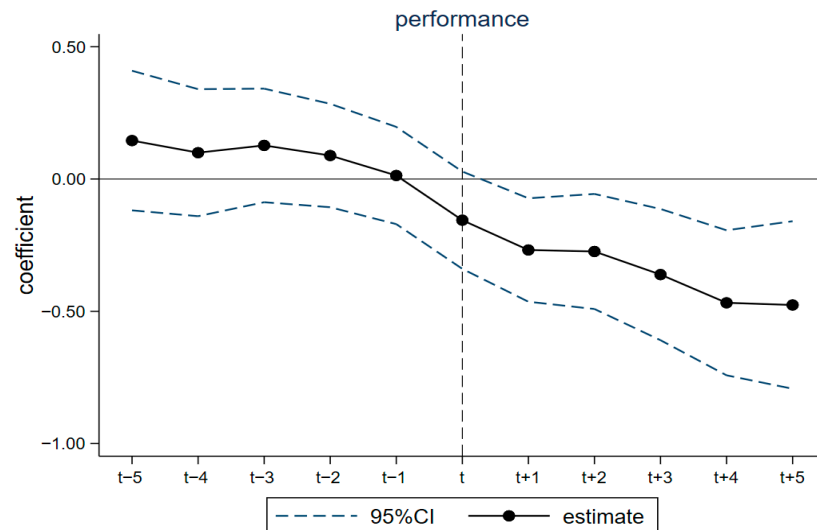


Figure 3. Parallel trend test results.

4.3. Robustness Tests

4.3.1. Placebo Test

This study employs a placebo test based on randomization inference to mitigate potential interference from random factors or unobservable variables [64]. Specifically, we randomly assign the *DID* treatment indicator across cities 500 times and re-estimate the benchmark model for each iteration to obtain a distribution of placebo coefficients. Figure 4 displays the kernel density distribution of these 500 placebo estimates. The pseudo-estimated coefficients concentrate around zero with approximately normal distribution characteristics, and the vast majority are not statistically significant. The vertical dashed line marks the actual baseline *DID* coefficient (-0.213), which lies far in the left tail of the placebo distribution. Among the 500 placebo estimates, none is smaller than or equal to the actual coefficient, yielding a randomization inference p -value of 0.000 ($p < 0.01$). This result confirms that the benchmark regression finding is highly unlikely to be driven by random factors or sample selection bias, and that the policy effect remains statistically significant well beyond the 1% level under the more stringent randomization inference criterion.

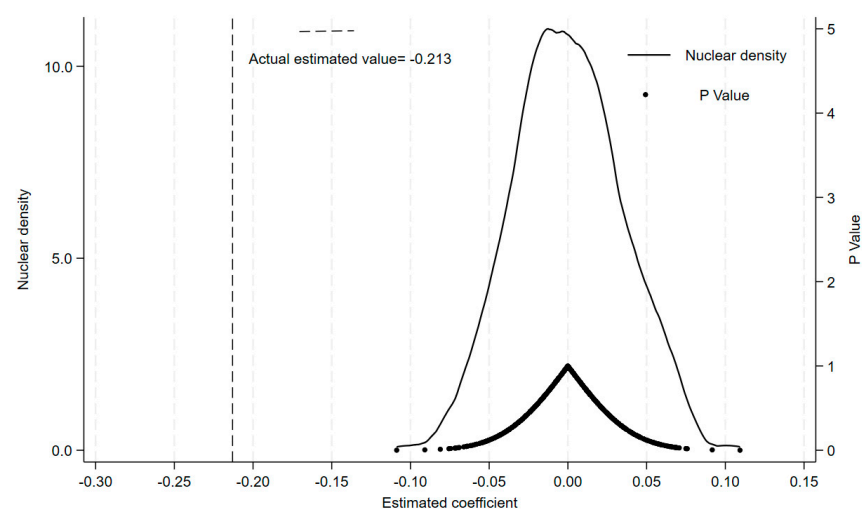


Figure 4. Placebo test results.

4.3.2. Propensity Score Matching

Pilot cities may not be randomly selected but rather determined by environmental governance pressure and economic development level. This non-random allocation could

create systematic differences between treatment and control groups, affecting estimates. To address this, we employ propensity score matching difference-in-differences (PSM-DID). Using a Logit model, we estimate each city's propensity score with matching variables including population size, economic development level, financial development, FDI, urbanization rate, and government fiscal expenditure. Through 1:4 nearest neighbor matching, we pair each treatment city with four control cities having the closest propensity scores within the common support region. Column (1) of Table 1 shows the regression results remain robust.

Table 1. Robustness test results.

Variables	PSM-DID	One-Period Lagged Regression	Excluding Provincial-Level Municipalities	Excluding the COVID-19 Period
	<i>SYOP</i>	<i>SYOP</i>	<i>SYOP</i>	<i>SYOP</i>
<i>DID</i>	−0.224 ** (0.095)		−0.220 *** (0.064)	−0.205 *** (0.070)
<i>DID</i> _{T-1}		−0.207 *** (0.064)		
_cons	−6.581 *** (1.376)	−7.463 *** (0.649)	−7.863 *** (0.624)	−7.542 *** (0.674)
<i>Control</i>	Yes	Yes	Yes	Yes
<i>Year</i>	Yes	Yes	Yes	Yes
<i>Province</i>	Yes	Yes	Yes	Yes
<i>N</i>	1236	4258	4466	3733
<i>R</i> ²	0.676	0.664	0.644	0.675
<i>adj. R</i> ²	0.665	0.660	0.640	0.671
<i>F</i>	120.554	521.275	559.366	508.754

Note: Robust standard errors are in parentheses; *** and ** indicate significance at the 1%, 5%, and 10% levels, respectively. Control variables, time and province are controlled for below.

4.3.3. One-Period Lagged Regression

To exclude reverse causality whereby pollution and carbon emission changes may influence policy implementation decisions, we incorporate the one-period lagged policy variable into the regression model. Column (2) of Table 1 shows the lagged *DID* coefficient is −0.207 (1% level), demonstrating that policy effect identification is not disturbed by reverse causality and enhancing result reliability.

4.3.4. Excluding Provincial-Level Municipalities

Beijing, Shanghai, Tianjin, and Chongqing, as provincial-level municipalities at the same administrative level as provincial governments, exhibit significant differences from ordinary prefecture-level cities in fiscal capacity, policy resources, and environmental governance requirements. To test conclusion applicability, we re-estimate the benchmark model excluding these four municipalities. Column (3) of Table 1 shows the *DID* coefficient is −0.220 (1% level), highly consistent with the benchmark regression (−0.213), indicating research conclusions are not driven by provincial-level municipality characteristics but equally applicable to ordinary prefecture-level cities.

4.3.5. Excluding the COVID-19 Period

The COVID-19 pandemic had unprecedented impacts on China's economic and social development. Strict prevention measures led to substantial economic fluctuations, abnormal energy consumption changes, and significant non-policy impacts on environmental quality and carbon emissions, interfering with accurate policy effect identification.

We therefore exclude 2020–2022 data to eliminate pandemic shock impacts. Column (4) of Table 1 shows that the DID coefficient is -0.205 (1% level), highly consistent with benchmark results, indicating that main conclusions are not affected by the pandemic shock. The negative effect of air quality ecological compensation policy on synergistic pollution and carbon governance robustly exists during normal economic periods.

4.4. Mechanism Analysis

Benchmark regression results have confirmed that air quality ecological compensation policy significantly promotes synergistic governance of air pollution and carbon emissions. In this section, we further explore the potential mechanisms driving this effect. As indicated in the aforementioned Section 2.2 on action mechanisms, air quality ecological compensation policy may promote synergistic governance of pollution reduction and carbon mitigation by reshaping local governments' industrial development preferences, incentivizing green technological innovation, and enhancing energy utilization efficiency. Based on this theoretical framework, we examine the impact of air quality ecological compensation policy on advanced industrial structure, green technological innovation capacity, and energy consumption intensity in pilot cities. The test results are as follows:

Column (2) of Table 2 presents the advanced industrial structure mechanism results. The DID coefficient is 0.253 (1% level), indicating the policy significantly promotes advanced industrial structure in pilot cities. The increase reflects the relative expansion of the tertiary sector compared to the secondary sector, with the economic center shifting from resource-intensive manufacturing toward knowledge- and service-intensive industries. The fiscal reward and punishment mechanism effectively drives local governments to advance industrial structure to achieve synergistic pollution and carbon governance, confirming Hypothesis 2.

Table 2. Mechanism test results.

Variables	(1)	(2)	(3)	(4)
	<i>SYOP</i>	<i>Ais</i>	<i>Gpatent</i>	<i>EI</i>
<i>DID</i>	-0.213^{***} (0.064)	0.253^{***} (0.014)	0.047^* (0.026)	-0.012^{***} (0.004)
<i>_cons</i>	-7.853^{***} (0.624)	-0.248^{***} (0.146)	-22.689^{***} (0.274)	0.617^{***} (0.038)
<i>Control</i>	Yes	Yes	Yes	Yes
<i>Year</i>	Yes	Yes	Yes	Yes
<i>Province</i>	Yes	Yes	Yes	Yes
<i>N</i>	4534	4556	4556	4534
<i>R²</i>	0.667	0.641	0.875	0.443
<i>adj. R²</i>	0.663	0.638	0.874	0.436
<i>F</i>	558.755	635.940	3021.940	104.400

Note: Robust standard errors are in parentheses; *** and * indicate significance at the 1%, 10%, and 10% levels, respectively. Control variables, time and province are controlled for below.

Column (3) presents the results for the green technological innovation capacity mechanism. The DID coefficient is 0.047 (significant at the 10% level), indicating that the policy enhances green technological innovation capacity in pilot cities. The increase in green invention patent applications reflects strengthened innovation investment in clean production, pollution control, and low-carbon energy technologies, and captures improvements in the quality of green innovation. This enhancement in innovation capacity contributes to reducing pollutant and carbon emissions through a portfolio of source-reduction and end-of-pipe technologies whose individual carbon implications differ but whose aggregate effect is synergistically positive, supporting Hypothesis 3.

Column (4) presents the energy intensity mechanism results. The *DID* coefficient is -0.012 (1% level), indicating the policy significantly reduces energy consumption intensity in pilot cities. Cities experience significant declines in energy consumption per unit GDP, reflecting the joint effect of improved energy utilization efficiency and the ongoing transition of energy consumption structure toward cleaner sources. These two sub-channels are both direct consequences of the fiscal reward-and-penalty mechanism: the threat of fiscal penalties for air quality deterioration simultaneously incentivizes local governments to strengthen energy-saving supervision over high-energy-consuming enterprises and to accelerate the substitution of clean energy for coal. As such, the coefficient captures the full scope of the policy's energy-related behavioral response rather than efficiency improvement alone. The decline simultaneously reduces atmospheric pollutants and carbon dioxide emissions through fossil fuel consumption reduction, achieving synergistic governance and confirming Hypothesis 4.

Mechanism testing reveals three core pathways. First, advanced industrial structure (*Ais*) reduces the proportion of high-emission industries through economic structure upgrading. Second, the enhancement of green technological innovation capacity (*Gpatent*), promotes cleaner production and pollution control technologies, thereby reducing emissions. Third, the decline in energy intensity (*EI*) lowers fossil fuel consumption through energy efficiency improvements and the policy-driven shift in energy use toward cleaner sources. These pathways jointly operate to translate fiscal incentives into effective environmental governance, exhibiting complementary and reinforcing effects.

5. Heterogeneity Analysis

Environmental economics theory and empirical research indicate that environmental policy effects are often constrained by local governance capacity, resource endowments, and development stages [65,66]. In China, with its vast territory and extremely unbalanced regional development, policy effect heterogeneity is especially prominent.

This section examines heterogeneity across four dimensions: government fiscal capacity, economic development level, urbanization degree, and green coverage area in built-up areas, representing local governments' resource mobilization capacity, industrial transformation foundation, spatial governance efficiency, and ecological environment baseline. By systematically examining differentiated policy performance across city types, we provide scientific evidence for formulating differentiated ecological compensation standards, optimizing resource allocation, and promoting balanced regional environmental governance capacity development. Sample cities are divided into three groups—low (below the 25th percentile), middle (between the 25th and 75th percentiles), and high (above the 75th percentile)—and separate regressions are conducted for each group. Results are shown in Table 3.

5.1. Heterogeneity of Government Support Intensity

Columns (1)–(3) of Table 3 display grouped regression results by government support intensity. In high-support cities, the *DID* coefficient is -0.349 (1% level); in middle-support cities, the coefficient is -0.231 (5% level); in low-support cities, the coefficient is 0.044 and insignificant. This gradient pattern indicates that the synergistic pollution and carbon mitigation effect strengthens progressively with government support intensity, and is absent in the most fiscally constrained cities.

Table 3. Heterogeneity analysis results.

Variables	Low GOV	Mid GOV	High GOV	Low GDP	Mid GDP	High GDP	Low UR	Mid UR	High UR	Low GC	Mid GC	High GC
	<i>SYOP</i>	<i>SYOP</i>	<i>SYOP</i>	<i>SYOP</i>	<i>SYOP</i>	<i>SYOP</i>	<i>SYOP</i>	<i>SYOP</i>	<i>SYOP</i>	<i>SYOP</i>	<i>SYOP</i>	<i>SYOP</i>
<i>DID</i>	0.044 (0.123)	−0.231 ** (0.089)	−0.349 *** (0.127)	−0.288 (0.198)	−0.201 *** (0.077)	−0.149 * (0.089)	−0.162 (0.152)	−0.231 *** (0.082)	−1.558 *** (0.090)	−0.378 ** (0.159)	−0.207 ** (0.087)	0.021 (0.108)
<i>_cons</i>	−11.981 *** (1.268)	−7.167 *** (1.117)	−10.647 *** (2.582)	−15.685 *** (1.754)	−7.298 *** (1.326)	−1.948 (1.197)	−15.183 *** (1.690)	−9.452 *** (0.987)	1.206 (0.892)	−11.278 *** (1.347)	−8.886 *** (0.889)	−6.836 *** (1.306)
<i>Control</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Year</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>Province</i>	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>N</i>	1137	2263	1134	1139	2262	1132	1132	2275	1127	1140	2264	1128
<i>R²</i>	0.645	0.622	0.614	0.571	0.648	0.736	0.387	0.640	0.552	0.707	0.688	0.684
<i>adj. R²</i>	0.630	0.613	0.597	0.552	0.640	0.723	0.374	0.632	0.547	0.693	0.681	0.670
<i>F</i>	159.469	156.041	53.257	76.357	158.626	114.060	92.492	185.248	151.931	174.605	285.422	110.854

Note: Robust standard errors are in parentheses; ***, ** and * indicate significance at the 1%, 5%, and 10% levels, respectively. Control variables, time and province are controlled for below.

This heterogeneity has two plausible explanations. First, high government fiscal capacity reflects deeper local government involvement in public affairs. Such regions can provide sufficient financial guarantees for environmental infrastructure, enterprise green transformation subsidies, and pollution control technology promotion. The ecological compensation mechanism thus complements existing fiscal resources, creating a mutually reinforcing dynamic between the policy's incentive signal and local implementation capacity. Second, in cities where government plays a more dominant role in resource allocation, fiscal instruments can more effectively guide industrial restructuring and technological innovation, amplifying the policy's incentive effects [67,68]. Conversely, low fiscal capacity cities face a binding resource constraint: even when the policy's incentive signal is received, the lack of complementary fiscal resources limits the scope and speed of behavioral adjustment, constraining the translation of incentives into environmental outcomes.

5.2. Heterogeneity of Economic Development Level

Columns (4)–(6) of Table 3 report the results grouped by economic development level. In middle-development cities, the *DID* coefficient is -0.201 (significant at the 1% level); in high-development cities, the coefficient is -0.149 (significant at the 10% level); in low-development cities, the coefficient is -0.288 but not statistically significant. This pattern indicates that the policy is more effective in promoting synergistic pollution reduction and carbon mitigation in cities with moderate to high levels of economic development, while the lack of statistical significance in low-development cities suggests substantial heterogeneity in policy responses across less developed areas.

This heterogeneity stems from differences in governance capacity and industrial foundation across development stages. Economically developed cities have typically progressed further in industrialization, possess more advanced industrial structures with higher tertiary and high-tech industry proportions, and face lower marginal costs of environmental governance. These cities also possess stronger technological innovation capacity, more complete environmental management systems, and higher public environmental awareness, enabling faster and more effective responses to policy incentives [69]. Less developed cities, by contrast, remain in earlier industrialization stages where economic growth depends heavily on resource-intensive and energy-intensive industries. In such contexts, the structural adjustment costs required to improve air quality are substantially higher, and the tension between environmental governance and economic development more acute, limiting the policy's capacity to induce the multi-dimensional adjustments necessary for synergistic governance.

5.3. Heterogeneity of Urbanization Level

Columns (7)–(9) of Table 3 present results grouped by urbanization level. In high-urbanization cities, the *DID* coefficient is -1.558 (1% level); in middle-urbanization cities, the coefficient is -0.231 (1% level); in low-urbanization cities, the coefficient is -0.162 but insignificant. This gradient pattern reveals that the synergistic governance effect strengthens substantially with urbanization level, with the most pronounced effect in highly urbanized cities where agglomeration economies and regulatory infrastructure are most developed.

This difference reflects urbanization's impact on environmental governance efficiency. In highly urbanized areas, enterprise spatial agglomeration enables environmental regulators to supervise densely distributed pollution sources at relatively low administrative costs. The intensive spatial layout and complete infrastructure facilitate centralized pollution control facility construction and operation. Population agglomeration also makes the health impacts of pollution more salient, strengthening public environmental demands

and prompting local governments to prioritize policy implementation [70]. Additionally, agglomeration effects reduce per-unit pollution control costs for enterprises, creating more favorable conditions for compliance [71]. In low-urbanization regions, geographically dispersed pollution sources significantly increase supervision difficulty and cost. Dispersed population and industrial distribution prevent environmental governance from achieving economies of scale, and administrative resource constraints limit effective oversight of numerous small-scale, scattered emission sources [70].

5.4. Heterogeneity of Green Coverage Area in Built-Up Areas

Columns (10)–(12) of Table 3 present results grouped by the green coverage area in built-up areas. In low-green-coverage cities, the *DID* coefficient is -0.378 (5% level); in middle-green-coverage cities, the coefficient is -0.207 (5% level); in high-green-coverage cities, the coefficient is 0.021 and insignificant. This declining gradient reveals that the synergistic governance effect is strongest in cities with the lowest green coverage and diminishes as green coverage increases, with no significant effect in cities that already enjoy the most favorable green environment.

This pattern contrasts with the other three heterogeneity dimensions, where the least-advantaged cities show insignificant effects. For green coverage, the opposite obtains: cities with less green space—typically characterized by denser industrial development, more intensive land use, and worse ambient air quality—exhibit the strongest policy response. Two mechanisms explain this reversal. First, cities with low green coverage face greater environmental governance pressure, as their baseline air quality is further from regulatory targets, making the fiscal penalties under ecological compensation more binding and the fiscal rewards more attainable through marginal improvement. The resulting stronger fiscal incentive drives more aggressive behavioral adjustments, including accelerated pollution control investment and industrial restructuring. Second, cities with high green coverage have likely already achieved relatively favorable environmental conditions through prior governance efforts, leaving less room for additional improvement from the ecological compensation mechanism—a pattern consistent with diminishing marginal returns to environmental policy intervention [22]. Additionally, the natural filtering and absorption capacity provided by extensive green coverage may partially substitute for the policy-induced emission reduction pathways, further attenuating the incremental effect of fiscal incentives in these cities.

5.5. Summary and Implications of Heterogeneity Results

The heterogeneity analysis reveals a consistent but nuanced pattern across four dimensions. For fiscal capacity, economic development, and urbanization, the policy's synergistic effect is strongest in cities endowed with greater fiscal capacity and higher urbanization, while across economic development levels the effect peaks in middle-development cities rather than following a strictly monotonic gradient. In all three of these dimensions, the least-advantaged subgroup (low fiscal support, low GDP, low urbanization) exhibits a statistically insignificant policy effect, indicating that the compensation mechanism fails to reach the cities that arguably need it most. The green coverage dimension introduces a contrasting pattern: the policy effect is strongest in cities with the lowest green coverage, moderate in mid-coverage cities, and insignificant in high-coverage cities, suggesting that cities with worse environmental baselines have more room for policy-induced improvement while cities with already favorable ecological conditions face diminishing marginal returns. This regularity carries three interrelated implications.

First, it raises concerns about environmental equity. The cities where the policy shows no significant effect are often those facing the most pressing environmental challenges,

limited governance resources, and the greatest need for policy support. If the ecological compensation mechanism functions effectively only where institutional and economic preconditions are already favorable, it risks reinforcing rather than alleviating regional environmental governance disparities, a dynamic sometimes characterized as the “Matthew effect” [72]. This finding qualifies the policy’s overall average treatment effect estimated in Section 4.1: while the pooled estimate is statistically significant, it likely reflects stronger effects in advantaged cities combined with weaker or negligible effects in disadvantaged ones. The average effect should therefore not be interpreted as indicating uniform policy effectiveness across all Chinese cities.

Second, the heterogeneity results suggest that the policy’s transmission channels may operate with different intensity depending on local conditions. Although data limitations preclude a formal interaction analysis between heterogeneity dimensions and individual mechanisms within the scope of this study, the pattern is consistent with a plausible interpretation: fiscal capacity constraints may limit the ability of disadvantaged cities to fund the industrial restructuring, green innovation investment, and energy efficiency improvements through which the policy’s synergistic effects are transmitted. If this interpretation is correct, it implies that supplementary fiscal transfers or technical assistance targeting the mechanism channels may be necessary to extend the policy’s benefits to resource-constrained regions.

Third, the government fiscal support dimension offers a concrete opportunity for quantitative policy calibration. Of the four heterogeneity dimensions, fiscal support intensity is the most directly actionable for redesigning the compensation mechanism, because the policy itself operates as a fiscal instrument: the parameter that policymakers can adjust is the per-unit compensation coefficient, and the government support variable most closely proxies the local fiscal leverage that amplifies or attenuates the compensation signal. By contrast, economic development level, urbanization rate, and green coverage area, while important moderators, cannot be directly manipulated through adjustments to the compensation formula. Exploiting this dimension, the subgroup coefficients form a monotonically declining gradient within the fiscal capacity dimension: -0.349 for high-support cities, -0.231 for middle-support cities, and an insignificant 0.044 for low-support cities. The ratio $| -0.349 | / | -0.231 | \approx 1.51$ indicates that the policy’s marginal effect in fiscally strong cities is approximately 1.5 times that in cities with moderate fiscal capacity. This ratio quantifies the “fiscal amplification premium” between adjacent tiers and provides a data-grounded lower bound for the compensation rate adjustment needed to narrow the inter-tier effectiveness gap. The calibration benchmark suggests that the current uniform-coefficient design underestimates the fiscal signal required for resource-constrained cities, and that a tiered compensation structure—with higher per-unit rates for cities in lower fiscal-capacity tiers—would be necessary to move toward equalized policy responsiveness across groups. The precise magnitude of the required multiplier for the weakest tier will depend on further empirical investigation into whether their fiscal constraints are merely attenuating or fully binding, which we flag as an important direction for future research.

6. Conclusions and Policy Recommendations

6.1. Summary of Findings

This study assesses the impact of air quality ecological compensation policy on synergistic pollution reduction and carbon mitigation governance, using our city-level panel dataset and a multi-period difference-in-differences framework. Our findings yield contributions at both the scientific and applied levels.

At the scientific level, the central finding is that the policy, despite containing no explicit carbon-related assessment criteria, produces a statistically significant reduction

in the composite pollution carbon emissions index ($\beta = -0.213$, $p < 0.01$), confirmed by an alternative weighted-average specification ($\beta = -0.153$, $p < 0.01$) and robust to multiple sensitivity checks. This result demonstrates that fiscal incentives tied to air quality governance can generate carbon-mitigation co-benefits through the behavioral and structural adjustments they induce, extending the co-benefits literature beyond policies that directly target carbon emissions. The mechanism analysis identifies three interrelated transmission channels—industrial structure upgrading, green technological innovation, and energy intensity reduction—that operate simultaneously to translate fiscal incentives into environmental governance outcomes.

At the applied level, the heterogeneity analysis reveals that the policy's synergistic benefits are unevenly distributed. For fiscal capacity, economic development, and urbanization, the effect concentrates in better-endowed cities and is statistically insignificant in the least-advantaged subgroups, raising environmental equity concerns. The green coverage dimension shows the opposite pattern: cities with worse environmental baselines benefit most, consistent with diminishing marginal returns. A particularly actionable applied result emerges from the fiscal capacity dimension, where the subgroup coefficients form a monotonically declining gradient (-0.349 , -0.231 , and an insignificant 0.044), yielding a “fiscal amplification premium” ratio of approximately 1.51 between adjacent tiers. This ratio provides a quantitative benchmark for calibrating differentiated compensation standards—a finding that directly informs the policy recommendations in Section 6.2.

6.2. Policy Recommendations

Three recommendations follow from the empirical findings.

First, the heterogeneity results provide direct justification for differentiated compensation standards. The current uniform-coefficient design implicitly assumes that all cities possess comparable capacity to translate fiscal incentives into governance outcomes, an assumption our analysis does not support. For fiscally constrained and less developed cities, higher compensation payment rates or more achievable improvement thresholds could reduce the mismatch between policy expectations and local implementation capacity. Concretely, provincial governments could adopt tiered compensation coefficients that account for baseline fiscal capacity when calculating reward and penalty amounts. Importantly, to preserve incentives for continuous improvement, the tiered scheme should be designed as a dynamic ladder rather than a static support arrangement. Cities that move from a more constrained or environmentally stressed tier to a less problematic tier could benefit from lower compliance pressure, reduced exposure to fiscal penalties, and greater fiscal flexibility to shift resources from short-term compliance measures toward longer-term industrial upgrading, green innovation, and energy-efficiency improvement. In this sense, upward movement across tiers should itself be treated as a policy reward, because it reflects stronger local governance capacity and a more sustainable path toward pollution–carbon synergies. At the same time, a tiered compensation scheme may increase administrative complexity by requiring periodic tier reassessment, additional monitoring, and closer coordination across levels of government. To prevent the system from generating excessive bureaucracy or discretionary implementation, tier assignment should rely on a limited set of transparent indicators, fixed review cycles, and standardized reporting procedures. In this way, policy differentiation can improve incentive precision without imposing disproportionate administrative costs.

Second, the mechanism analysis suggests that directing compensation funds toward specific transmission channels could enhance policy effectiveness. Rather than leaving the allocation of environmental governance resources entirely to local discretion, establishing dedicated guidance funds that earmark a portion of compensation revenues for industrial

upgrading projects, green technology R&D subsidies, and energy efficiency retrofits could accelerate the structural and technological adjustments through which synergistic effects are transmitted. A dynamic monitoring framework that periodically assesses the performance of funded projects and adjusts allocation standards accordingly would help ensure that resources are directed toward the most effective channels.

Third, the finding that a policy without carbon-related criteria nonetheless produces measurable carbon co-benefits suggests an opportunity for policy integration. Explicitly incorporating carbon emissions or energy intensity indicators into the compensation assessment framework would strengthen the currently indirect carbon incentive and create a more comprehensive governance instrument. At the same time, expanding the assessment scope in this way may increase monitoring, reporting, and verification burdens, especially in regions where carbon accounting capacity remains limited. A prudent approach would therefore be to introduce such indicators gradually, beginning with relatively observable proxies such as energy intensity, while establishing unified accounting standards, digitalized data-sharing mechanisms, and clear interdepartmental responsibilities to contain administrative costs and avoid overlapping supervision. Linking this expanded compensation system with carbon trading mechanisms and environmental taxation could form a multi-dimensional incentive framework that addresses both pollution and carbon objectives through coordinated rather than fragmented policy instruments.

Beyond the Chinese context, the findings carry broader implications for sustainable development policy design in other developing and emerging economies. The core insight—that fiscal incentives anchored to observable air quality indicators can generate carbon-mitigation co-benefits through induced structural, technological, and efficiency adjustments—is not inherently specific to China’s institutional setting. Many developing countries face the same dual challenge of air pollution and climate change, share the “common root and source” linkage between pollutants and CO₂ through fossil fuel dependence, and possess limited administrative capacity for implementing complex carbon pricing or emissions trading systems. The ecological compensation model offers a potentially transferable alternative: by leveraging existing air quality monitoring infrastructure and intergovernmental fiscal transfer mechanisms, it provides a lower-barrier entry point for achieving carbon co-benefits without requiring the construction of dedicated carbon measurement, reporting, and verification systems. However, several scope conditions qualify this generalizability. First, the policy’s effectiveness depends critically on the fiscal capacity and governance infrastructure of subnational governments, as our heterogeneity analysis demonstrates: cities with weak fiscal capacity and low urbanization show no significant policy response. Countries or regions where subnational fiscal systems are underdeveloped or where intergovernmental transfer mechanisms are absent may not be able to replicate the incentive structure. Second, the strength of the pollution carbon linkage varies with energy mix: in economies where fossil fuels constitute a smaller share of primary energy, the indirect carbon co-benefits of air quality governance may be correspondingly weaker. Third, the specific institutional design—provincial coordination of inter-city transfers, quarterly assessment cycles, and simultaneous monitoring of multiple pollutants—reflects China’s particular administrative hierarchy and may require adaptation to different governance architectures. These scope conditions do not diminish the policy’s relevance but rather define the boundary conditions under which the Chinese experience is most likely to be transferable.

6.3. Future Research Prospects

While this study provides robust evidence that air quality ecological compensation policy generates synergistic pollution reduction and carbon mitigation co-benefits at the

aggregate city level, it cannot rule out the possibility that part of the observed improvement in treated cities reflects the spatial relocation of polluting industries rather than genuine emission elimination. Our heterogeneity analysis offers indirect but suggestive evidence on this concern. The policy's synergistic effect is statistically significant only in cities with strong fiscal capacity ($\beta = -0.349, p < 0.01$), higher economic development, and advanced urbanization ($\beta = -1.558, p < 0.01$), while it is insignificant in the least-advantaged subgroups across all three dimensions. This pattern is consistent with—though not conclusive evidence of—a pollution haven mechanism: economically and fiscally advantaged cities, possessing stronger regulatory enforcement capacity and greater resources for industrial restructuring, may achieve air quality improvements partly by displacing pollution-intensive enterprises toward jurisdictions with weaker governance capacity, lower regulatory stringency, or locations outside the provincial compensation assessment framework altogether. If such spatial displacement is substantial, the net environmental gains at the national level would be smaller than what our city-level estimates suggest, and the environmental burden on receiving regions—typically less developed cities already facing acute fiscal constraints and insignificant policy responses—could be exacerbated, deepening rather than alleviating the “Matthew effect” identified in Section 5.5. Moreover, our mechanism analysis showing that the policy significantly promotes industrial structure upgrading ($\beta = 0.253, p < 0.01$) cannot, with the current data, distinguish whether the relative expansion of tertiary industry in treated cities reflects genuine in situ industrial transformation or the outward migration of secondary-sector enterprises. Testing this hypothesis requires firm-level or establishment-level data that track enterprise relocation decisions, entry and exit patterns across jurisdictions, and emission changes at both origin and destination locations, combined with spatial econometric methods capable of identifying cross-jurisdictional pollution spillovers. This constitutes an important direction for future research and would provide critical evidence for assessing whether the policy's synergistic benefits represent genuine aggregate emission reductions or partially reflect a geographical redistribution of environmental burdens.

A second limitation concerns the theoretically ambiguous role of fiscal pressure in mediating the policy's effects, a complexity that our current empirical framework captures only partially. Our heterogeneity results on government fiscal capacity reveal a monotonically declining gradient—from $\beta = -0.349$ ($p < 0.01$) in high-support cities, through $\beta = -0.231$ ($p < 0.05$) in middle-support cities, to an insignificant 0.044 in low-support cities—which we interpret in Section 5.1 primarily as reflecting resource constraints that limit the translation of fiscal incentives into governance outcomes. However, fiscal pressure may theoretically exert dual and opposing effects on policy implementation. On the one hand, the threat of compensation penalties creates stronger marginal incentives for cities under greater fiscal strain, precisely because penalty payments represent a larger share of their limited available revenues; in this sense, fiscal scarcity amplifies the policy's incentive signal. On the other hand, precisely because these cities have fewer discretionary fiscal resources, their capacity to fund the industrial restructuring (the *Ais* channel, $\beta = 0.253, p < 0.01$), green technology adoption (the *Gpatent* channel, $\beta = 0.047, p < 0.10$), and energy efficiency improvements (the *EI* channel, $\beta = -0.012, p < 0.01$) through which the policy's synergistic effects are transmitted is more constrained; in this sense, fiscal scarcity attenuates the policy's implementation capacity. The insignificant effect observed in low fiscal capacity cities could therefore reflect either a binding resource constraint that prevents behavioral adjustment despite strong incentive pressure, or a situation in which the incentive-amplifying and capacity-constraining effects of fiscal pressure approximately offset each other, yielding a net null effect. Disentangling these two channels requires more granular fiscal data—such as the decomposition of local government expenditure

across environmental governance, industrial subsidies, and infrastructure investment—and potentially quasi-experimental variation in fiscal transfers that is orthogonal to the compensation mechanism itself. Resolving this ambiguity would not only deepen the theoretical understanding of how fiscal instruments operate under heterogeneous institutional conditions, but also provide more precise guidance for calibrating the tiered compensation coefficients proposed in Section 6.2: if the primary barrier is a binding resource constraint, then supplementary fiscal transfers or earmarked environmental governance funds may be more effective than simply raising per-unit compensation rates; if instead the incentive and constraint effects are offsetting, then a combination of higher compensation rates and complementary capacity-building support would be required to activate the policy’s transmission channels in resource-constrained cities.

Author Contributions: Conceptualization, Q.B. and Z.C.; methodology, Z.C.; software, Q.B.; validation, Q.B. and Z.C.; formal analysis, Q.B.; investigation, Q.B.; resources, Z.C.; data curation, Q.B.; writing—original draft preparation, Q.B.; writing—review and editing, Z.C.; visualization, Q.B.; supervision, Z.C. All authors have read and agreed to the published version of the manuscript.

Funding: Key Program of the Henan Provincial Science and Technology Research and Development Plan Joint Fund (grant numbers: 245200810028).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author, Qingxuan Bu (bqx15936862262@gmail.com), upon reasonable request.

Acknowledgments: The authors thank the Editors and anonymous reviewer for their evaluation and very important comments that helped to increase the quality of this paper. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. The descriptive statistics of variables.

Variables	Std	Obs	P50	Mean	Min	Max
<i>SYOP</i>	1.767	4534	11.800	11.730	5.754	17.230
<i>PE</i>	0.040	4534	0.018	0.033	0.000	0.433
<i>CE</i>	0.112	4556	0.040	0.080	0.000	1.000
<i>SYOP-W</i>	1.000	4534	−0.357	0.000	−0.710	8.245
<i>DID</i>	0.477	4556	0.000	0.351	0.000	1.000
<i>POP</i>	0.676	4556	5.943	5.906	3.400	8.136
<i>GDP</i>	0.764	4556	10.570	10.600	8.126	12.880
<i>FIN</i>	1.239	4556	2.143	2.463	0.560	21.300
<i>FDI</i>	0.003	4556	0.002	0.003	0.000	0.029
<i>UR</i>	0.202	4556	0.332	0.384	0.075	1.000
<i>GOV</i>	0.099	4556	0.164	0.189	0.044	1.027
<i>GC</i>	5.834	4556	40.691	39.634	17.280	50.200
<i>Ais</i>	0.578	4556	0.888	1.023	0.094	6.387
<i>Gpatent</i>	1.834	4556	3.638	3.783	0.000	10.084
<i>EI</i>	0.116	4556	0.079	0.102	0.006	4.176

Table A2. Benchmark regression results.

Variables	(1) PE	(2) CE	(3) SYOP	(4) SYOP-W
<i>DID</i>	−0.029 *** (0.001)	−0.017 *** (0.004)	−0.213 *** (0.064)	−0.153 *** (0.031)
<i>POP</i>	0.009 *** (0.001)	0.058 *** (0.002)	1.053 *** (0.032)	0.520 *** (0.016)
<i>GDP</i>	−0.002 *** (0.001)	0.079 *** (0.003)	1.276 *** (0.050)	0.706 *** (0.024)
<i>FIN</i>	−0.004 *** (0.001)	0.007 *** (0.001)	0.025 (0.019)	0.064 *** (0.009)
<i>FDI</i>	1.206 *** (0.202)	−1.979 *** (0.401)	−17.446 ** (7.269)	−17.832 *** (3.575)
<i>UR</i>	0.014 *** (0.004)	0.041 *** (0.007)	0.914 *** (0.130)	0.384 *** (0.064)
<i>GOV</i>	−0.089 *** (0.007)	0.100 *** (0.016)	−2.389 *** (0.288)	0.910 *** (0.142)
<i>_cons</i>	0.032 ** (0.012)	−1.143 *** (0.034)	−7.853 *** (0.624)	−10.940 *** (0.307)
<i>Year</i>	Yes	Yes	Yes	Yes
<i>Province</i>	Yes	Yes	Yes	Yes
<i>N</i>	4534	4556	4534	4534
<i>R2</i>	0.441	0.745	0.667	0.748
<i>adj. R2</i>	0.437	0.742	0.663	0.745
<i>F</i>	269.683	432.814	558.756	436.438

Note: Robust standard errors are in parentheses; *** and ** indicate significance at the 1%, 5%, and 10% levels, respectively. Control variables, time and province are controlled for below.

References

1. Duman, Z.; Mao, X.; Cai, B.; Zhang, Q.; Chen, Y.; Gao, Y.; Guo, Z. Exploring the spatiotemporal pattern evolution of carbon emissions and air pollution in Chinese cities. *J. Environ. Manag.* **2023**, *345*, 118870. [\[CrossRef\]](#) [\[PubMed\]](#)
2. Miyazaki, K.; Bowman, K. Predictability of fossil fuel CO₂ from air quality emissions. *Nat. Commun.* **2023**, *14*, 1604. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Bistline, J.E.; Blanford, G.; Grant, J.; Knipping, E.; McCollum, D.L.; Nopmongcol, U.; Yarwood, G. Economy-wide evaluation of CO₂ and air quality impacts of electrification in the United States. *Nat. Commun.* **2022**, *13*, 6693. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Wang, H.; Liu, T.; Xu, H.; Dai, E.; Hou, H. Synergy of carbon-pollution-ecology—The future of synergetic reduction of pollution and carbon emissions. *Environ. Impact Assess. Rev.* **2025**, *114*, 107931. [\[CrossRef\]](#)
5. WMO Confirms 2024 as Warmest Year on Record at About 1.55 °C Above Pre-Industrial Level. Available online: <https://wmo.int/news/media-centre/wmo-confirms-2024-warmest-year-record-about-155degc-above-pre-industrial-level> (accessed on 10 January 2026).
6. Brauer, M.; Roth, G.A.; Aravkin, A.Y.; Zheng, P.; Abate, K.H.; Abate, Y.H.; Amani, R. Global burden and strength of evidence for 88 risk factors in 204 countries and 811 subnational locations, 1990–2021: A systematic analysis for the Global Burden of Disease Study 2021. *Lancet* **2024**, *403*, 2162–2203. [\[CrossRef\]](#)
7. Wang, Y.; Wang, A.; Zhai, J.; Tao, H.; Jiang, T.; Su, B.; Fischer, T. Tens of thousands additional deaths annually in cities of China between 1.5 C and 2.0 C warming. *Nat. Commun.* **2019**, *10*, 3376. [\[CrossRef\]](#)
8. Geng, G.; Liu, Y.; Liu, Y.; Liu, S.; Cheng, J.; Yan, L.; Zhang, Q. Efficacy of China’s clean air actions to tackle PM_{2.5} pollution between 2013 and 2020. *Nat. Geosci.* **2024**, *17*, 987–994. [\[CrossRef\]](#)
9. Huang, Z.; Li, X.; Chen, J.; Zhang, D. Does the Three-Year Action Plan for Winning the Blue Sky Defense Battle implementation enabling the high-quality development of regional energy? A quasi-natural experiment from China. *Energy* **2024**, *312*, 133405. [\[CrossRef\]](#)
10. Zeng, S.; Fu, Q.; Haleem, F.; Shen, Y.; Peng, W.; Ji, M.; Xu, Y. China’s carbon trading pilot policy, economic stability, and high-quality economic development. *Humanit. Soc. Sci. Commun.* **2024**, *11*, 1107. [\[CrossRef\]](#)
11. Wang, Q.; Zhan, J.; Zhang, H.; Cao, Y.; Yang, Z.; Wu, Q.; Otho, A.R. China’s carbon emissions trading market: Current situation, impact assessment, challenges, and suggestions. *Land* **2025**, *14*, 1582. [\[CrossRef\]](#)

12. Xu, L.; Wang, S.; Yu, H. Does China's Low-Carbon City Pilot Policy Effectively Reduce Carbon Emissions? A Dual Perspective on Carbon Emissions and Efficiency. *Systems* **2026**, *14*, 170. [\[CrossRef\]](#)
13. Kim, S.Y.; Kerr, G.H.; van Donkelaar, A.; Martin, R.V.; West, J.J.; Anenberg, S.C. Tracking air pollution and CO₂ emissions in 13,189 urban areas worldwide using large geospatial datasets. *Commun. Earth Environ.* **2025**, *6*, 311. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Huang, X.; Srikrishnan, V.; Lamontagne, J.; Keller, K.; Peng, W. Effects of global climate mitigation on regional air quality and health. *Nat. Sustain.* **2023**, *6*, 1054–1066. [\[CrossRef\]](#)
15. Cheng, X.; Yu, Z.; Gao, J.; Liu, Y.; Jiang, S. Governance effects of pollution reduction and carbon mitigation of carbon emission trading policy in China. *Environ. Res.* **2024**, *252*, 119074. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Zhu, J.; Wu, S.; Xu, J. Synergy between pollution control and carbon reduction: China's evidence. *Energy Econ.* **2023**, *119*, 106541. [\[CrossRef\]](#)
17. Wen, W.; Deng, Z.; Ma, X.; Xing, Y.; Pan, C.; Liu, Y.; Shen, L. Analysis of the synergistic benefits of typical technologies for pollution reduction and carbon reduction in the iron and steel industry in the Beijing–Tianjin–Hebei region. *Sci. Rep.* **2024**, *14*, 12413. [\[CrossRef\]](#)
18. Tang, R.; Zhao, J.; Liu, Y.; Huang, X.; Zhang, Y.; Zhou, D.; Wang, H. Air quality and health co-benefits of China's carbon dioxide emissions peaking before 2030. *Nat. Commun.* **2022**, *13*, 1008. [\[CrossRef\]](#)
19. Vandyck, T.; Keramidas, K.; Kitous, A.; Spadaro, J.V.; Van Dingenen, R.; Holland, M.; Saveyn, B. Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges. *Nat. Commun.* **2018**, *9*, 4939. [\[CrossRef\]](#)
20. Cui, L.; Duan, H.; Mo, J.; Song, M. Ecological compensation in air pollution governance: China's efforts, challenges, and potential solutions. *Int. Rev. Financ. Anal.* **2021**, *74*, 101701. [\[CrossRef\]](#)
21. Weng, S.; Tao, W.; Cui, L. Can ecological compensation reduce air pollution? New evidence from resource-based cities in China. *Energy Sources Part B Econ. Plan. Policy* **2024**, *19*, 2351803. [\[CrossRef\]](#)
22. Chang, D.; Zhang, Z.; Song, H.; Wu, J.; Wang, X.; Dong, Z. "Icing on the cake" or "fuel delivered in the snow"? Evidence from China on ecological compensation for air pollution control. *Environ. Impact Assess. Rev.* **2024**, *109*, 107620. [\[CrossRef\]](#)
23. Zhang, X.; Wu, L.; Zhang, Z. Does Air Quality Ecological Compensation Improve Total Factor Energy Efficiency?—A Quasi-Natural Experiment from 282 Cities in China. *Sustainability* **2024**, *16*, 6067. [\[CrossRef\]](#)
24. Liu, Y.; Zhang, J.; Zhu, L. Pay for air pollution: Ecological compensation policy and corporate investment. *Int. Rev. Financ. Anal.* **2025**, *97*, 103808. [\[CrossRef\]](#)
25. Chang, L.; Wang, J.; Liu, H. The role of atmospheric quality ecological compensation in improving the effects of pollution tax policy. *J. Clean. Prod.* **2025**, *484*, 144595.
26. Wang, C.; Ling, J.; Liu, Y.; Liu, B.; Deng, N. Can air quality ecological compensation improve environmental welfare performance? Based on the "Win–Win–Win" perspective of economy–ecology–welfare. *J. Clean. Prod.* **2025**, *489*, 144604. [\[CrossRef\]](#)
27. Pigou, A.C. *The Economics of Welfare*; Macmillan: London, UK, 1920.
28. Porter, M.E.; Linde, C.V.D. Toward a new conception of the environment-competitiveness relationship. *J. Econ. Perspect.* **1995**, *9*, 97–118. [\[CrossRef\]](#)
29. Hicks, J. *The Theory of Wages*; Springer: Berlin, Germany, 1963.
30. Acemoglu, D.; Aghion, P.; Bursztyn, L.; Hémous, D. The environment and directed technical change. *Am. Econ. Rev.* **2012**, *102*, 131–166. [\[CrossRef\]](#)
31. Wong, C.; Karplus, V.J. China's war on air pollution: Can existing governance structures support new ambitions? *China Q.* **2017**, *231*, 662–684. [\[CrossRef\]](#)
32. Oates, W.E. *Fiscal Federalism*; Harcourt Brace Jovanovich: New York, NY, USA, 1972.
33. Oates, W.E. An essay on fiscal federalism. *J. Econ. Lit.* **1999**, *37*, 1120–1149. [\[CrossRef\]](#)
34. Shi, Q.; Zheng, B.; Zheng, Y.; Tong, D.; Liu, Y.; Ma, H.; Zhang, Q. Co-benefits of CO₂ emission reduction from China's clean air actions between 2013–2020. *Nat. Commun.* **2022**, *13*, 5061. [\[CrossRef\]](#)
35. Kuznets, S. Modern economic growth: Findings and reflections. *Am. Econ. Rev.* **1973**, *63*, 247–258.
36. Lewis, W.A. Economic development with unlimited supplies of labour. *Manch. Sch.* **1954**, *22*, 139–191. [\[CrossRef\]](#)
37. Xu, N.; Zhang, F.; Xuan, X. Impacts of industrial restructuring and technological progress on PM_{2.5} pollution: Evidence from prefecture-level cities in China. *Int. J. Environ. Res. Public Health* **2021**, *18*, 5283. [\[CrossRef\]](#) [\[PubMed\]](#)
38. Feng, Y.; Wu, H. How does industrial structure transformation affect carbon emissions in China: The moderating effect of financial development. *Environ. Sci. Pollut. Res.* **2022**, *29*, 13466–13477. [\[CrossRef\]](#)
39. Gu, R.; Li, C.; Li, D.; Yang, Y.; Gu, S. The impact of rationalization and upgrading of industrial structure on carbon emissions in the Beijing–Tianjin–Hebei urban agglomeration. *Int. J. Environ. Res. Public Health* **2022**, *19*, 7997. [\[CrossRef\]](#)
40. Yi, M.; Wang, Y.; Yan, M.; Fu, L.; Zhang, Y. Government R&D subsidies, environmental regulations, and their effect on green innovation efficiency of manufacturing industry: Evidence from the Yangtze River economic belt of China. *Int. J. Environ. Res. Public Health* **2020**, *17*, 1330.

41. Bai, Y.; Song, S.; Jiao, J.; Yang, R. The impacts of government R&D subsidies on green innovation: Evidence from Chinese energy-intensive firms. *J. Clean. Prod.* **2019**, *233*, 819–829.
42. Ma, N.; Liu, P.; Xiao, Y.; Tang, H.; Zhang, J. Can green technological innovation reduce hazardous air pollutants?—An empirical test based on 283 cities in China. *Int. J. Environ. Res. Public Health* **2022**, *19*, 1611. [\[CrossRef\]](#)
43. Zeng, S.; Li, G.; Wu, S.; Dong, Z. The impact of green technology innovation on carbon emissions in the context of carbon neutrality in China: Evidence from spatial spillover and nonlinear effect analysis. *Int. J. Environ. Res. Public Health* **2022**, *19*, 730. [\[CrossRef\]](#)
44. Kaya, Y.; Yokobori, K. (Eds.) *Environment, Energy, and Economy: Strategies for Sustainability*; United Nations University Press: Tokyo, Japan, 1997.
45. Azhgaliyeva, D.; Liu, Y.; Liddle, B. An empirical analysis of energy intensity and the role of policy instruments. *Energy Policy* **2020**, *145*, 111773. [\[CrossRef\]](#)
46. Guo, R.; Yuan, Y. Different types of environmental regulations and heterogeneous influence on energy efficiency in the industrial sector: Evidence from Chinese provincial data. *Energy Policy* **2020**, *145*, 111747. [\[CrossRef\]](#)
47. Hong, M.; Chen, S.; Zhang, K. Impact of the “low-carbon city pilot” policy on energy intensity based on the empirical evidence of Chinese cities. *Front. Environ. Sci.* **2021**, *9*, 717737. [\[CrossRef\]](#)
48. Chen, J.; Zhou, C.; Wang, S.; Li, S. Impacts of energy consumption structure, energy intensity, economic growth, urbanization on PM2.5 concentrations in countries globally. *Appl. Energy* **2018**, *230*, 94–105. [\[CrossRef\]](#)
49. Hou, J.; Yang, S.; Fan, G.; Xu, H. The impact of energy consumption on carbon emissions intensity in China: Evidence from a dynamic panel quantile regression model. *Int. J. Low-Carbon Technol.* **2024**, *19*, 268–288. [\[CrossRef\]](#)
50. Shan, Y.; Liu, J.; Liu, Z.; Shao, S.; Guan, D. An emissions-socioeconomic inventory of Chinese cities. *Sci. Data* **2019**, *6*, 190027. [\[CrossRef\]](#)
51. Wang, Y.; Chen, H.; Long, R.; Sun, Q.; Jiang, S.; Liu, B. Has the sustainable development planning policy promoted the green transformation in China’s resource-based cities? *Resour. Conserv. Recycl.* **2022**, *180*, 106181. [\[CrossRef\]](#)
52. Bastardo, N.; Jacquart, P.; Antonakis, J. Effect of crises on charisma signaling: A regression discontinuity design. *Leadersh. Q.* **2024**, *35*, 101590. [\[CrossRef\]](#)
53. Arkhangelsky, D.; Athey, S.; Hirshberg, D.A.; Imbens, G.W.; Wager, S. Synthetic difference-in-differences. *Am. Econ. Rev.* **2021**, *111*, 4088–4118. [\[CrossRef\]](#)
54. Cinelli, C.; Forney, A.; Pearl, J. A crash course in good and bad controls. *Sociol. Methods Res.* **2024**, *53*, 1071–1104. [\[CrossRef\]](#)
55. Ting, J. Mediating and moderating effects in empirical studies of causal inference. *China Ind. Econ.* **2022**, *5*, 100–120.
56. Wang, D.; Li, Y.; Yang, X.; Zhang, Z.; Gao, S.; Zhou, Q.; Guo, Z. Evaluating urban ecological civilization and its obstacle factors based on integrated model of PSR-EVW-TOPSIS: A case study of 13 cities in Jiangsu Province, China. *Ecol. Indic.* **2021**, *133*, 108431. [\[CrossRef\]](#)
57. Lin, B.; Zhou, Y. Measuring the green economic growth in China: Influencing factors and policy perspectives. *Energy* **2022**, *241*, 122518. [\[CrossRef\]](#)
58. Ma, Y.; Yao, W.; Jiang, L.; Xue, Y.W. Impact of China’s green finance reform and innovation pilot zone policies on urban pollution and carbon emission reduction and their mechanisms. *China Popul. Resour. Environ.* **2024**, *34*, 45–55.
59. Jia, Q.; Li, Q. Synergistic effect of pollution control and carbon reduction driven by new quality productive forces and its mechanisms. *China Popul. Resour. Environ.* **2025**, *35*, 80–90.
60. Yu, T.; Zhang, X. The impact of fintech development and advanced industrial structure on regional criminal offenses. *Financ. Res. Lett.* **2025**, *87*, 109061. [\[CrossRef\]](#)
61. Ling, F.; Zhen, H.; Wang, C.; Li, J.; Zhao, J. Environmental protection strategic alliance and enterprise green innovation. *Humanit. Soc. Sci. Commun.* **2025**, *12*, 1726. [\[CrossRef\]](#)
62. Yan, D.; Ren, X.; Kong, Y.; Ye, B.; Liao, Z. The heterogeneous effects of socioeconomic determinants on PM2.5 concentrations using a two-step panel quantile regression. *Appl. Energy* **2020**, *272*, 115246. [\[CrossRef\]](#)
63. Wang, J.; Zhang, G. Can environmental regulation improve high-quality economic development in China? The mediating effects of digital economy. *Sustainability* **2022**, *14*, 12143. [\[CrossRef\]](#)
64. Bertrand, M.; Duflo, E.; Mullainathan, S. How much should we trust differences-in-differences estimates? *Q. J. Econ.* **2004**, *119*, 249–275. [\[CrossRef\]](#)
65. Qi, Y.; Yin, A.; Chen, J.; Yang, C.; Zhan, P. Motivating for environmental protection: Evidence from county officials in China. *World Dev.* **2024**, *184*, 106760. [\[CrossRef\]](#)
66. Li, P.; Lu, Y.; Peng, L.; Wang, J. Information, incentives, and environmental governance: Evidence from China’s ambient air quality standards. *J. Environ. Econ. Manag.* **2024**, *128*, 103066. [\[CrossRef\]](#)
67. Wang, S.; Zhang, Z.; Zhou, Z.; Zhong, S. The carbon emission reduction effect of green fiscal policy: A quasi-natural experiment. *Sci. Rep.* **2024**, *14*, 20317. [\[CrossRef\]](#)

68. López, R.; Galinato, G.I.; Islam, A. Fiscal spending and the environment: Theory and empirics. *J. Environ. Econ. Manag.* **2011**, *62*, 180–198. [[CrossRef](#)]
69. Xu, L.; Fan, M.; Yang, L.; Shao, S. Heterogeneous green innovations and carbon emission performance: Evidence at China's city level. *Energy Econ.* **2021**, *99*, 105269. [[CrossRef](#)]
70. Zhang, C.; Tao, R.; Yue, Z.; Su, F. Regional competition, rural pollution haven and environmental injustice in China. *Ecol. Econ.* **2023**, *204*, 107669. [[CrossRef](#)]
71. Wu, J.; Segerson, K.; Wang, C. Is environmental regulation the answer to pollution problems in urbanizing economies? *J. Environ. Econ. Manag.* **2023**, *117*, 102754. [[CrossRef](#)]
72. Zhang, H.; Dou, W. Impact of air pollution prevention and control on urban green economy efficiency: Evidence from China. *Sci. Rep.* **2024**, *14*, 27905. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.