frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 26 June 2024
DOI 10.3389/fenvs.2024.1430031

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RECEIVED 09 May 2024
ACCEPTED 06 June 2024
PUBLISHED 26 June 2024

CITATION
Wang M, Wang Y, Yang Z and Guo B (2024), Does energy-consuming rights trading policy achieve urban pollution and carbon reduction? A quasi-natural experiment from China.
Front. Environ. Sci. 12:1430031.
doi: 10.3389/fenvs.2024.1430031

Does energy-consuming rights trading policy achieve urban pollution and carbon reduction? A quasi-natural experiment from China

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Energy-consuming rights trading (ECRT) policy represents a critical policy instrument for China striving to achieve its “dual carbon” objectives, captivating significant attention for its potential to reduce pollution and carbon emissions. This study utilizes panel data from 290 Chinese cities spanning 2010 to 2021, leveraging the ECRT policy as a quasi-natural experiment. Employing Difference-in-Differences (DID) and Propensity Score Matching-Difference-in-Differences (PSM-DID) methodologies, we assess the effect of the ECRT policy on urban pollution and carbon reduction levels. The findings indicate: 1) Relative to non-demonstration cities, the ECRT policy significantly enhances pollution and carbon reduction levels in demonstration cities; this conclusion remains robust after rigorous testing. 2) Heterogeneity analysis indicates that the policy’s effect on pollution and carbon reduction is more significant in the central and western regions, and particularly evident in key and resource-based cities. 3) Mechanism tests demonstrate that the policy facilitates urban pollution and carbon reduction by cultivating green technological innovation and industrial structure upgrading. Therefore, to further advance the ECRT policy, it is necessary to expand the breadth, depth, and flexibility of policy implementation, while also optimizing environmental regulations to fully leverage the system’s potential in enhancing urban pollution and carbon emissions.

KEYWORDS

energy-consuming rights trading policy, entropy-weighted TOPSIS model, difference-in-differences model, green technological innovation, industrial structure upgrading, China

1 Introduction

With the persistent advancement of economic and social development, particularly the rapid acceleration of industrialization, the global energy demand has witnessed a surge in both its rate and magnitude. According to the BP Statistical Review of World Energy 2023, global primary energy consumption reached 604.04 exajoules, marking a 1.3% increase from the 2019 level. Specifically, fossil fuels accounted for 82% of the consumption (BP statistical review of world energy, 2023). However, such significant reliance on fossil fuels has given rise to a spectrum of environmental concerns, including air pollution and ecological degradation (Khan et al., 2020; Li and Hu, 2020). The “Climate Change 2021: The

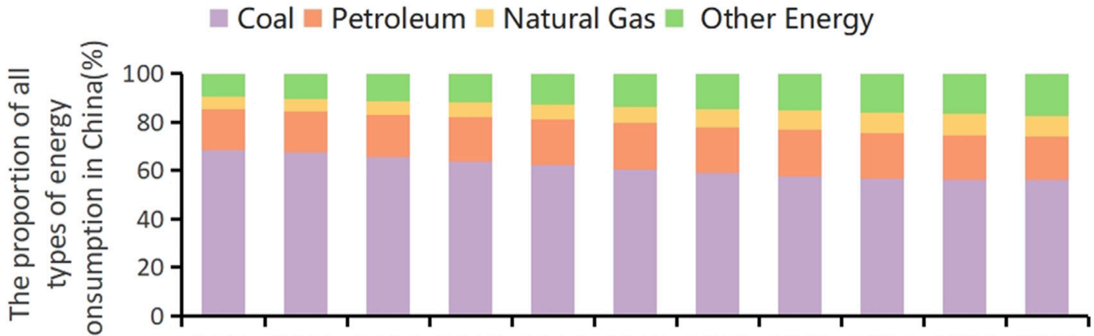

FIGURE 1
Energy consumption structure in China from 2012 to 2022.

Physical Science Basis" report compiled by the Intergovernmental Panel on Climate Change (IPCC) demonstrates that the average surface temperature from 2011 to 2020 surpassed pre-industrial levels by 1.1°C, accompanied by a continuous increase in the frequency and intensity of extreme weather events, posing significant threats to both environmental security and human health (Intergovernmental Panel on Climate C, 2023).

The majority of countries, including China, are experiencing an upward trend in carbon dioxide emissions (Shaari et al., 2021). China's role as the leading global consumer of energy has profound implications for the global environment. The nation's energy consumption and its ensuing pollution emissions issues have become a focal point for academic communities globally (Fatima et al., 2021; Bangjun et al., 2022; Meo et al., 2023; Xiao and Peng, 2023). As illustrated in Figure 1, China's energy mix relies heavily on coal, crude oil, and natural gas, supplemented by other sources such as hydropower and nuclear power.

China's characteristics of resource endowment have long been shaped by "an abundance of coal coupled with limited oil and natural gas reserves". In this light, and combined with an early economic development model characterized by high energy consumption, high emissions, and high pollution, fossil fuels are entrenched as the dominant energy source—notwithstanding their negative environmental impact. While the proportion of coal in the energy mix has steadily declined between 2012 and 2022, it remains significant (Suo et al., 2024). In 2022, China's total energy consumption reached 5.41 billion tons of standard coal equivalent, with fossil fuels—coal, petroleum, and natural gas—accounting for over 80% of this consumption. This continued reliance on fossil fuels poses a considerable challenge, contributing significantly to the country's environmental pollution problems. The "2022 China Environmental Status Report" indicates that among 339 Chinese cities, 126 (37.2%) failed to meet the environmental air quality standards. More specifically, 57 cities exceeded the limit for one pollutant, 31 for two pollutants, and 38 for three pollutants (Ministry of Ecology and Environment of China, 2022). Besides, China's overall environmental performance ranked 160th out of 180 countries in the 2022 Environmental Performance Index (EPI) report. The country also received low rankings for air quality, specifically in terms of environmental particulate matter and other related indicators (Zhong et al., 2024). As the world's largest developing nation, China faces significant gaps in environmental governance compared to developed countries and some emerging economies. Therefore, China faces immense pressure to address environmental challenges and navigate the dual constraints of resource scarcity and environmental degradation (Li et al., 2019). Therefore, a pressing imperative for achieving green and low-carbon development in China is to enhance energy efficiency and establish a development model characterized by low energy consumption, minimal pollution, and reduced emissions, thereby contributing to pollution and carbon reduction.

In response, the Chinese government has implemented a series of measures, including policies for pollutant discharge rights trading and carbon emission rights trading. During the 13th Five-Year Plan period, the "Four Revolutions and One Cooperation" energy security strategy offered guidance for China's energy development in the new era. Building on the pollutant discharge rights trading and carbon emission rights trading policies, the "Overall Plan for Ecological Civilization System Reform" introduced in 2015 first proposed the concept of energy rights. In 2016, pilot projects for energy-consuming right trading (ECRT) policy were initiated in Zhejiang, Fujian, Henan, and Sichuan provinces. The ECRT policy is based on the total energy consumption indicator (typically measured over a 1-year period). This trading occurs in a controlled region where energy-using units are allowed to trade legally obtained energy consumption quotas. The ECRT policy, similar to the European Union's white certificate trading system, emphasizes source control and utilizes the market for optimal resource allocation (Zhang et al., 2023a). Its aim is to achieve "dual control" of total energy consumption and intensity, offering a new pathway for pollution and carbon reduction.

Considering the significant theoretical and practical implications of the ECRT policy, this paper empirically evaluates and discusses several critical yet insufficiently explained issues: Firstly, how will the implementation of the ECRT policy impact the level of pollution and carbon reduction in cities? Secondly, through what mechanisms can pollution and carbon reduction be achieved? Thirdly, does the ECRT policy produce significant differences in pollution and carbon reduction effects across cities with different urban hierarchies, resource endowments, and geographical locations? Addressing these questions will enrich the empirical research on the effects of the ECRT policy, contributing significantly to the advancement of the energy rights system, promoting harmonious coexistence between humans and nature, and thus facilitating the green transformation of the economy and society. Meanwhile, as a developing nation, China's efforts in pollution and carbon reduction offer a valuable model for other developing countries. These efforts highlight China's commitment to supporting global sustainable development through collaborative initiatives.

This study produces several marginal contributions to the existing literature. First, while most existing studies measure urban low-carbon development utilizing carbon emissions volume or carbon emission efficiency, this study innovatively employs an entropy weight-TOPSIS model. This model evaluates a city's environmental pollution index, which is then multiplied by carbon emissions to represent the city's progress in coordinated pollution and carbon reduction efforts. Second, from the policy perspective of the energy use rights trading scheme, this study utilizes data from 2011 to 2021 across prefecture-level cities to systematically examine the effect of this policy on pollution and carbon reduction. This analysis not only enriches the existing research on the ECRT policy but also provides new evidence to support the promotion of this system and the enhancement of coordinated pollution and carbon reduction efforts in cities. Finally, in terms of research content, the main contributions include three aspects: First, recognizing the common origin of carbon dioxide and other atmospheric pollutants, this paper analyzes the policy's effects on other atmospheric pollutants, thus broadening the scope of research on the environmental effects of the ECRT policy. Second, by considering the differences in geographical location, urban hierarchy, and resource endowments of cities, the study explores the heterogeneous effects of the ECRT policy on urban pollution and carbon reduction, aiding in a targeted understanding of the mechanisms through which the ECRT policy affects urban pollution and carbon reduction. Third, the paper employs a mechanism test model to analyze the role of energy intensity in the ECRT policy's effect on urban pollution and carbon reduction, contributing to a deeper understanding of the mechanisms through which the ECRT policy affects urban pollution and carbon reduction.

The rest of the paper is organized as follows. The second section contains the relevant literature review five and research hypotheses. The third section shows the model setup, data sources, variable definitions, and descriptive statistics. The fourth section reports the empirical results and robustness tests. The fifth section further tests the heterogeneity of cities from three aspects: city locations, city level, and urban resource endowment. It also explores the mechanism of ECRT policy in demonstration cities. The last one, there are conclusions and policy recommendations.

2 Literature review and research hypotheses

Environmental regulatory policies represent one of the effective means to address environmental issues, with their theoretical foundations and practical applications mutually strengthening each other. The "public good" nature of the environment means that spontaneous price mechanisms struggle to address the external diseconomies produced by environmental pollution during economic activities. Methods to address these externalities include the imposition of environmental taxes and the definition of property rights. Originating from Pigou's (Pigou, 1920) 1920 theory, which proposed the use of taxation to resolve the externalities of environmental pollution, environmental taxes represent a typical governmental control approach. The property rights theorem, introduced by Coase (Coase, 2013) in 1960, suggests that by clearly and appropriately defining initial property rights, economic value can be assigned to environmental resources, and resource allocation can be optimized through the market to achieve Pareto efficiency. Building on Coase's theorem, research on environmental regulatory policies has expanded. Dales (Dales, 1970) first applied the concept of property rights to pollution control, introducing "pollution rights trading." Montgomery (Montgomery, 1972), utilizing mathematical economic methods, demonstrated the cost-effectiveness of market-based pollution rights trading systems. In 1976, the U.S. Environmental Protection Agency (EPA) applied pollution rights trading in practice, followed by Germany, Australia, China, and other countries gradually establishing their pollution rights trading policies. Carbon emission rights trading, as an extension of pollution rights trading, was formally established as a new market-based mechanism to address greenhouse gas emissions following the signing of the Kyoto Protocol in 1997. The European Union established the Greenhouse Gas Emission Trading System (EU-ETS) in 2005, applying carbon emission rights trading on a large scale in practice (Brouwers et al., 2016), which has since enriched research in various countries. The ECRT policy is based on pollution rights trading and carbon emission rights trading policies, and it belongs to market-incentive environmental regulatory policies.

China's environmental regulatory policies primarily include command-and-control and market-incentive environmental policies (Xiong et al., 2020). Researchers have noted that China's early environmental governance was based on command-and-control environmental policies (Ren et al., 2018), where the government directly manages and controls, with "mandatory" characteristics such as market access, restrictive use, and price controls. These policies, while strict, often result in displacement effects from corporate production exceeding the benefits brought by innovation, with high implementation costs and relatively low operational efficiency. Market-incentive environmental policies, on the other hand, can internalize externalities through market transactions and economic incentives. China currently has four market-incentive environmental regulatory policies: ECRT policy, pollution rights trading, carbon emission rights trading, and water rights trading. Compared to command-and-control, market-incentive policies are less costly (Jaffe et al., 2003) and offer more significant incentives in reducing pollutant emission intensity (Kathuria, 2006). Market-based environmental regulations, represented by ECRT, pollution rights trading, and carbon emission rights trading, have become important policy tools for countries to address resource, environmental, and climate change issues. Among these, pollution rights trading and carbon emission rights trading are categorized under end-of-pipe management, while ECRT pertains to source control. Guo et al. (2024a) argued that environmental pollution taxes leverage the advantages of tax systems in market-based resource allocation, utilizing price signals to propel the development of a green and low-carbon economy.

Regarding the effect of environmental regulatory policies on pollution and carbon reduction from an end-of-pipe management perspective, extensive theoretical and empirical research has been conducted in China. This research has explored both the macro and micro effectiveness of environmental regulatory policies in reducing pollution and carbon emissions. Effectiveness includes the effectiveness of pollution rights trading mechanisms in pilot areas for reducing pollutants and the effectiveness of carbon trading policies in reducing carbon emissions.

For instance, Dong et al. (2019), Chai et al. (2022) utilized provincial data, Yan et al. (2020), Feng. (2020), Shen et al. (2023) utilized municipal-level data, and Zhang and Zhang. (2020) utilizing industry data, have empirically demonstrated at a macro level that pollution rights trading policies or carbon emission rights trading policies significantly reduce the emissions of pollutants and carbon dioxide. At the micro level, the focus has primarily been on enterprises, with Chen et al. (2018), Zhu et al. (2022) utilizing firm-level data to prove that end-of-pipe environmental regulatory policies significantly promote emission reductions in enterprises. However, differing opinions on the effectiveness of these reductions exist, such as Shin's (Shin, 2013) view that China lacks the prerequisites for policy innovation and diffusion, with policy imitation prevailing over innovation, thus limiting the effectiveness of emission rights trading policies in reducing pollution. Guo. (2018) argued that emission permit trading policies consist of multiple policy tools, which may conflict with each other, thereby affecting the overall policy implementation, and that excessive intervention by local governments casts doubt on the efficiency of carbon emission rights trading in reducing emissions. Overall, existing research generally agrees that environmental regulatory policies from an end-of-pipe management perspective significantly promote pollution and carbon reduction, yielding environmental dividends (Song et al., 2022).

The effect of ECRT policy on pollution and carbon reduction from a source control perspective is the focal point of this paper. However, empirical studies on this subject are currently limited, with most research utilizing provincial or corporate data and treating ECRT pilot policies as quasi-natural experiments. For instance, Wang (Wang X. et al., 2023) selected panel data from 30 provinces in China from 2011 to 2020, constructing a DID model with the ECRT pilot policy as a quasi-natural experiment, and through regression analysis demonstrated that the ECRT policy can significantly reduce carbon dioxide emissions and emission intensity. Yang et al. (2024), based on provincial panel data, employed a DID model to empirically analyze the carbon mitigation effects of the ECRT policy, confirming that it could significantly reduce carbon dioxide emissions in pilot provinces. Zhang et al. (2023b) offered empirical evidence of carbon mitigation from a micro perspective, utilizing a sample of Chinese carbon-emitting companies from 2011 to 2020 and employing the DID method to study whether the ECRT policy has a dual dividend effect on corporate economic performance and carbon emissions. They found that the ECRT policy could significantly reduce corporate carbon emissions through enhancing technological innovation, thereby achieving environmental dividends. Researchers have also analyzed municipal panel data, such as Wang K. et al. (2023), who utilized the DID method combined with municipal panel data to demonstrate that implementing the ECRT policy can reduce regional carbon emission intensity by encouraging corporate green technological innovation. In their heterogeneity analysis results, the carbon mitigation effects of the ECRT policy were significant in the eastern and central regions. Han et al. (2024), utilizing panel data from 266 Chinese cities, constructed a DID model to demonstrate that the ECRT policy resulted in a reduction of 84.8% in CO_2 and 34.5% in SO_2 in pilot cities compared to non-pilot cities. Compared to studies on environmental regulatory policies from an end-of-pipe management perspective, there are fewer empirical studies on the effect of ECRT pilot policies on pollution and carbon reduction, with most originating from provincial and corporate data and fewer exploring municipal-level data, neglecting the analysis of the reduction effects on atmospheric pollutants other than carbon dioxide. Based on the common origin of carbon dioxide and other atmospheric pollutants and the policy design objectives of the ECRT policy, which aims to promote pollution and carbon reduction at all levels, this paper proposes the following hypothesis.

H1: ECRT policy can significantly enhance a city's capacity for pollution and carbon reduction.

According to Porter's hypothesis, stringent environmental regulatory policies stimulate corporate green technological innovation (Porter and Linde, 1995). Green technological innovation, which adheres to ecological and economic standards (Gao et al., 2022a), has attributes of environmental friendliness, innovativeness, and efficiency, and its importance in sustainable development continues to grow (Zhang et al., 2022). Existing research largely agrees that green technological innovation has a positive effect on pollution and carbon reduction (Chen and Lee, 2020; Shan et al., 2021; Gao et al., 2022b; Dong et al., 2022; Yi et al., 2022), often measured by the number of low-carbon technologies and green invention patents applied for or held by production units. If the cost of green technological innovation for a production unit offsets environmental costs, it will opt for green technological innovation to enhance its market profitability and competitiveness. ECRT policy, focusing on source control, is a market-incentive environmental regulatory policy that internalizes the external environmental costs caused by production units. Under the control of total energy consumption and intensity in the region, pilot area governments are responsible for the allocation of energy rights quotas, periodically granting energy units initial energy rights quotas either freely or for a fee, with differential charges applied for excess usage. In the energy market, energy units are free to trade energy rights quotas. When the cost of energy rights quotas for high-energy-consuming units exceeds the cost of innovation, to offset compliance costs and maximize profits, they will increase investment in green technological innovation, actively engaging in it to enhance input-output levels; otherwise, they will reduce output or purchase quotas to fulfill their energy-saving and consumption-reducing responsibilities (Li and Zhao, 2023). Currently, researchers have utilized empirical methods to prove that ECRT policy significantly incentivizes green technological innovation. For instance, Zhang and Chen. (2023), Shao and Liu. (2024), based on micro-level data from Chinese enterprises, have empirically demonstrated that the ECRT policy significantly promotes green technological innovation among Chinese enterprises. At the urban level, Guo et al. (2023a), utilizing panel data from 254 Chinese cities from 2005 to 2019, combined with the DID model and Super-SBM method, verified that ECRT policy can enhance urban green development efficiency through green technological innovation. In summary, ECRT policy has an incentivizing effect on corporate green technological innovation, and green technological innovation is critical in promoting pollution and carbon reduction. Based on this, the following hypothesis is proposed.

H2: ECRT policy can promote urban pollution and carbon reduction by cultivating green technological innovation.

Advancing the upgrade of industrial structures is a crucial aspect of supply-side structural reforms (Gao et al., 2022b). Upgrading industrial structures deepens the transformation of traditional industrial sectors, optimizes their input structures, enhances resource utilization efficiency, and facilitates cleaner and more efficient production processes. The significance of industrial structure upgrading in elevating industrial development levels and accelerating pollution and carbon reduction processes is well recognized (Zhou et al., 2013; Dong et al., 2020). Regarding the effect of ECRT policy on industrial structure upgrading, empirical studies have demonstrated that ECRT policy is conducive to promoting industrial structure upgrades (Zhang and Zhou, 2024). The effect of these policies on industrial structure upgrading is twofold: firstly, ECRT policy, by classifying energy rights quotas, constrains high-energy-consuming industries, guiding them to adjust production models, optimize resource allocation, and facilitate the transfer of resources to low-energy-consuming industries, thereby compelling industrial transformation and upgrading (Xue and Zhou, 2022). Secondly, they offer significant market opportunities for emerging industries, leading to cluster effects of new industries, thus driving the development of high-tech industries and achieving the optimization and upgrading of industrial structures (Meng, 2023). In summary, ECRT policy is beneficial in promoting industrial structure upgrades, which can accelerate the process of pollution and carbon reduction. Based on this, the following hypothesis is proposed.

H3: ECRT policy can promote urban pollution and carbon reduction by cultivating the transformation and upgrading of industrial structures.

3 Research design

3.1 Model setup

3.1.1 Entropy-weighted TOPSIS model

The TOPSIS method is an optimal selection method based on the similarity to an ideal solution. Its principle involves utilizing the Euclidean distance to determine the proximity of the evaluation object to the best and worst solutions, thereby achieving a comprehensive evaluation ranking. The entropy-weighted TOPSIS method utilizes the entropy method to determine the weights of evaluation indicators, effectively overcoming the effects of subjective factors present in traditional TOPSIS methods when determining indicator weights. The entropy method allows for a more objective weighting of indicators, more reasonably reflecting the utility value of indicator data.

In environmental pollution management, the reduction of pollutants such as atmospheric pollutants, solid waste, and wastewater can bring about synergistic effects on carbon emission reduction and climate change (Chaudhry et al., 2021). Following the approach of Le et al. (Le et al., 2023), this paper adopts an enhanced entropy-weighted TOPSIS model to measure the environmental pollution index of various prefecture-level cities to represent the local ecological environment quality and degree of environmental pollution. The environmental pollution index calculation involves indicators of "three types of wastes" from 2010 to 2021 for 290 prefecture-level cities in China, specifically including the generation of general industrial solid waste (in ten thousand tons), carbon dioxide emissions from exhaust gases (in ten thousand tons), and total wastewater discharge (in ten thousand tons). The environmental pollution index is an inverse indicator; the higher its value, the more severe the city's environmental pollution and the lower the quality of its ecological environment. The calculation steps are as follows:

First, trend normalization of indicator data, $r_{ij} = \frac{x_{ij}}{min\, x_j}$, where i is the i-th evaluation indicator; j is the j-th evaluation year; x_{ij} is the judgment matrix of size $m \times n$, where $i = 1, 2, \cdots$, m; $j = 1, 2, \cdots$, n; r_{ij} is the normalized value of x_{ij}, R is represented as $(\mathrm{r_{ij}})_{\mathrm{m \times n}}$.

Second, calculate the information entropy e_j, $e_j = -k\sum_{i=1}^{m} f_{ij}\, ln\, f_{ij}$, $f_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}}$ ($\mathrm{k} = \frac{1}{ln\, m}$ is the Boltzmann constant).

Third, determine the weight values W_j, $W_j = \frac{1-e_j}{n-\sum_{j=1}^{n} e_j}$, $W_j \in [0, 1]$, and $\sum_{j=1}^{n} W_j = 1$.

Fourth, construct the weighted normalized decision matrix $Z = (z_{ij})_{m \times n} z_{ij} = W_j \times r_{ij}$.

Fifth, calculate the positive and negative ideal solutions and perform weighted processing on the normalized indicator values to construct the trend-normalized weighted normalized matrix Z, where Z^+ represents the positive ideal solution, and Z^- represents the negative ideal solution.

$$Z^+ = \left\{ \max_{1 \le i \le m} z_{ij} \middle| i = 1, 2, \cdots, m \right\} = \left\{ z_1^+, z_2^+, \cdots, z_n^+ \right\} \tag{1}$$

$$Z^- = \left\{ \min_{1 \le i \le m} z_{ij} \middle| i = 1, 2, \cdots, m \right\} = \left\{ z_1^-, z_2^-, \cdots, z_n^- \right\} \tag{2}$$

Sixth, calculate the Euclidean distances to the positive and negative ideal solutions, denoted as S^+ and S^-, respectively, representing the distances of each evaluation scheme to the positive and negative ideal solutions.

$$S^+ = \sqrt{\sum_{j=1}^{n} \left(Z_{ij} - Z_j^+ \right)^2} \, (i = 1, 2, \cdots, m) \tag{3}$$

$$S^- = \sqrt{\sum_{j=1}^{n} \left(Z_{ij} - Z_j^- \right)^2} \, (i = 1, 2, \cdots, n) \tag{4}$$

Finally, calculate the proximity to the ideal solution $(\mathrm{C_i})$, where $(\mathrm{C_i}) = \frac{\mathrm{S}_i^+}{\mathrm{S}_i^+ + \mathrm{S}_i^-}$. The proximity $(\mathrm{C_i})$ indicates the distance of the evaluation object to the positive ideal solution, i.e., the closeness of the evaluation target to the optimal solution, with $C_i \in [0, 1]$. Since all selected calculation indicators are inverse indicators, a C_i closer to one indicates that the city's ecological environment quality is closer to the worst level, while a C_i closer to 0 indicates that the city's ecological environment quality is closer to the optimal level.

3.1.2 DID model

Based on the Environmental Stress Model (IPAT), experimental and control groups are constructed from demonstration cities and policy implementation timings to test the policy effect of the carbon emission trading mechanism on pollution and carbon reduction. Drawing on the research method of Guo et al. (2024b), by introducing time dummy variables (*Time*) and city dummy variables (*Treat*), a Difference-in-Differences model is constructed as follows:

$$emission_{it} = \alpha_0 + \alpha_1 did_{it} + \alpha_c X_{it} + \sigma_t + \delta_i + \varepsilon_{it} \tag{5}$$

where $emission_{it}$ represents the pollution and carbon reduction level of city i in year t. The level of pollution and carbon reduction is characterized by the interaction term of carbon emissions and the environmental pollution index, both of which are inverse indicators. Constructing an interaction term reflects the overall reduction level and exhibits common source characteristics, aligning with the "common source of carbon and pollution" theory and fitting the holistic and systemic nature of pollution and carbon mitigation governance. did_{it} is a dummy variable for the ECRT policy; α_1 represents the policy effect of ECRT; X_{it} includes control variables; σ_t denotes fixed effects by year; δ_i represents city fixed effects; ε_{it} is the random disturbance term. This model effectively controls for characteristic differences and time trends between the experimental and control groups to some extent.

3.1.3 Variable description

3.1.3.1 Explained variable

Pollution and carbon reduction level (*emission*). Based on the availability of city level pollution and carbon reduction data and existing literature practices, this paper applies the Eqs 1–4 and characterizes the city's pollution and carbon reduction level utilizing the interaction term of carbon emissions and the environmental pollution index.

3.1.3.2 Explanatory variable

ECRT policy (*DID*). This variable is a dummy variable, taking a value of one in the year and following years when an ECRT policy is implemented in a city or its province, and 0 otherwise.

3.1.3.3 Control variables

In order to more accurately assess the effect of the ECRT policy on the city's pollution and carbon reduction levels, this paper controls for other factors that may affect city pollution and carbon emissions. These include city population size (*lnpop*), represented by the logarithm of the city's permanent population; economic development level (*lngdp*), represented by the logarithm of *per capita* GDP; education level (*lnedu*), represented by the logarithm of local government education spending; fiscal expenditure (*lnpfe*), represented by the logarithm of general budgetary expenditures of local finances; and foreign direct investment (*fin*), represented by the ratio of actual foreign direct investment to GDP.

TABLE 1 Descriptive statistics of the variables.

Variable	Obs	Mean	Std	Min	Max
Emission	3,480	0.097	0.061	0.004	0.621
DID	3,480	0.065	0.243	0	1
Lnpop	3,480	2.548	0.305	1.306	3.532
Lngdp	3,480	7.190	0.410	6.017	8.635
Lnedu	3,480	5.689	0.349	4.181	7.060
Lnfep	3,480	6.454	0.336	5.086	7.930
Fin	3,480	1.007	0.714	0.462	7.450
Ris	3,480	0.960	0.631	0.047	5.584
Patent	3,480	7.476	19.070	0.011	307.110

3.1.3.4 Mechanism variables

The transmission mechanism involves two variables: industrial structure upgrading (*ris*), indicated by the ratio of the value added of the tertiary sector to the secondary sector; and green technological innovation (*patent*), represented by *per capita* patent grants.

This study utilizes panel data from 290 prefecture-level and above cities in China from 2010 to 2021 to appraise the effect of the ECRT policy on urban pollution and carbon reduction. The data are derived from the "China City Statistical Yearbook," "China Environmental Statistical Yearbook," and various prefecture-level statistical yearbooks. Descriptive statistics of the variables are demonstrated in Table 1.

4 Empirical results and robustness tests

4.1 Baseline regression

The baseline regression results based on Eq. 5, as displayed in Table 2, assess the effect of the ECRT policy on pollution and carbon reduction. Column (1), controlling only for individual and year-fixed effects, demonstrates an interaction coefficient of −0.026, significant at the 1% level. Columns (2) to (7) add control variables sequentially to Column (1)'s model. After accounting for other factors, the core explanatory variable *DID* consistently demonstrates a significant negative coefficient, indicating a robust incentivizing effect of the ECRT policy on local pollution and carbon reduction, thereby enhancing environmental welfare for local residents. Therefore, Hypothesis H1 is confirmed.

Moreover, coefficients for permanent population and economic development level are significantly positive, suggesting that higher economic levels and larger populations increase carbon dioxide emissions. Conversely, coefficients for educational financial support, local fiscal support, and openness are significantly negative, indicating that increased educational and fiscal expenditures, along with greater openness, contribute to reducing carbon emissions and enhancing environmental conditions.

TABLE 2 Baseline regression results.

Variable	(1)	(2)	(4)	(5)	(6)	(7)
DID	−0.026*** (0.004)	−0.034*** (0.004)	−0.036*** (0.004)	−0.031*** (0.003)	−0.033*** (0.003)	−0.034*** (0.003)
Lnpop		0.069*** (0.003)	0.071*** (0.005)	0.072*** (0.005)	0.077*** (0.005)	0.071*** (0.005)
Lngdp			−0.058*** (0.004)	−0.074*** (0.004)	−0.119*** (0.005)	−0.117*** (0.005)
Lnedu				−0.038*** (0.003)	−0.025*** (0.003)	−0.026*** (0.003)
Lnfep					−0.106*** (0.007)	−0.099*** (0.007)
Fin						−0.006*** (0.001)
Con	0.099*** (0.001)	−0.076*** (0.008)	−0.227*** (0.017)	−0.108*** (0.019)	0.005 (0.020)	−0.017 (0.020)
Obs	3,480	3,480	3,480	3,480	3,480	3,480
R^2	0.014	0.132	0.186	0.225	0.279	0.282
Id-fixed	YES	YES	YES	YES	YES	YES
Year-fixed	YES	YES	YES	YES	YES	YES

Note: $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$; robust standard errors are in parentheses.

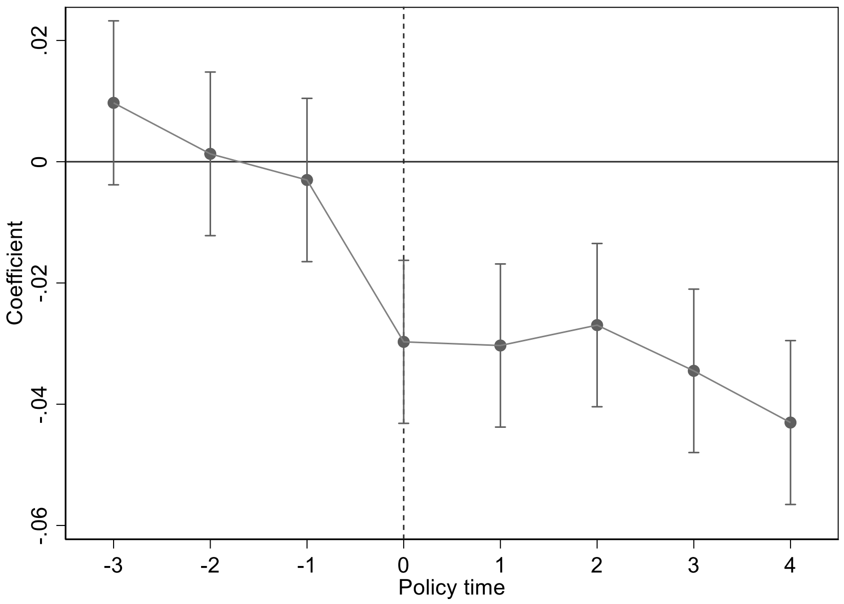

FIGURE 2
Parallel trend test graph.

4.2 Parallel trend test

A fundamental prerequisite for employing the Difference-in-Differences approach is satisfying the parallel trends assumption. This involves that, prior to the implementation of the ECRT policy, the experimental and control groups' urban pollution and carbon reduction levels must follow the same temporal trends. Following the methodology of Bi et al. (2019), an event study model is constructed as follows:

$$emission_{it} = \alpha_0 + \sum\nolimits_{k=-3,k\neq-1}^{4} \alpha_k did_{it}^{k} + \alpha_c X_{it} + \sigma_t + \delta_i + \varepsilon_{it} \qquad (6)$$

where i represents the city, and t denotes the year; did_{it}^{k} expresses a dummy variable representing the "event" of implementing the ECRT policy. The assignment rule for did_{it}^{k} is as follows: let u_i denote the policy implementation time point of the ECRT policy. If $t - u_i = k$, then $did_{it}^{k} = 1$; otherwise, $did_{it}^{k} = 0$. The setting of k is as follows: since the year of implementation is the 0th period, and the first batch was established in 2017, 2021 marks the fourth year of the pilot area's establishment, hence the maximum value of k in Eq. 6 is four; periods prior to the implementation of the ECRT policy extend back seven periods, but due to graphical limitations, this paper consolidates the 5th, 6th, and 7th years before the pilot into the

TABLE 3 PSM—DID regression results.

Variable	(1)	(2)
DID	−0.026*** (0.004)	−0.035*** (0.003)
Obs	3,480	3,480
R^2	0.014	0.278
Controls	No	YES
Id-fixed	YES	YES
Year-fixed	YES	YES

Note: $^*p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$; robust standard errors are in parentheses.

fourth year prior, and the 2nd year before the pilot is utilized as the base period to avoid multicollinearity, thus Eq. 6 does not include the dummy variable for $k = -1$. The coefficient α_k reflects the effect of the energy rights system before and after its implementation on the city's pollution and carbon reduction levels. If $k < 0$, the parameter α_k is not significantly different from 0, indicating that it has passed the parallel trend test, as depicted in Figure 2.

In Figure 2, the horizontal axis represents the number of years before and after the establishment of the ECRT policy, and the vertical axis represents the level of urban pollution and carbon reduction. It is evident that before the implementation of the energy rights system, the estimated values of α_k do not reject the null hypothesis of being zero, satisfying the parallel trends test. The regression coefficients after the implementation of the energy rights system indicate that cities implementing this policy experienced an immediate improvement in pollution and carbon reduction levels.

4.3 Analysis based on the PSM-DID method

Another prerequisite for utilizing the Difference-in-Differences approach is that the selection of experimental and control groups must satisfy the randomness assumption. This paper uses control variables as covariates and employs the Mahalanobis distance matching method to match samples of the experimental and control groups, thus reducing selection bias. Specifically, a Logit regression of the policy dummy variable on control variables is conducted to obtain propensity score matching values, with cities having similar scores as the control group. After obtaining matched experimental and control groups, it is necessary to test whether they satisfy the common support assumption, i.e., whether there are significant differences between the groups post-matching. The absence of significant differences in the test results post-matching confirms the effectiveness of the PSM-DID method employed in this study.

Meanwhile, the study evaluates the matching effect of the experimental and control groups through the probability density function graph of the propensity scores. The probability density distributions of the propensity scores for the matched experimental and control groups are closer post-matching compared to pre-matching, indicating a good matching effect.

After verifying the reliability of the PSM-DID method, further regression analysis is conducted, with results demonstrated in Table 3. Similar to the baseline regression results, the mean regression coefficients of the policy dummy variable are significantly negative, indicating that the implementation of the ECRT policy has a reducing effect on urban pollution and carbon emissions, thereby confirming the robustness of the baseline regression results.

4.4 Robustness tests

4.4.1 Placebo test

This study adopts the analytical approach of Yang et al. (2019) by conducting a placebo test as follows: Firstly, 55 cities are randomly selected from a total of 290 as a "pseudo-experimental group," assuming these cities have implemented the ECRT policy, with the remaining cities as the control group. Then, a random year is selected for the "pseudo-experimental group" as the policy year (pseudo policy time), and a "pseudo policy dummy variable" (interaction term) is created for regression analysis. This process is repeated 500 times, yielding 500 regression results, including regression coefficients, standard errors, and p-values for the "pseudo policy dummy variable." The distribution of the estimated coefficients is then plotted to appraise whether factors other than the ECRT policy significantly affect the cities' pollution and carbon reduction levels. As illustrated in Figure 3, the estimated coefficients from random grouping are primarily distributed around zero, significantly differing from the true coefficients, with most p-values exceeding 0.1. This indicates that the implementation of the ECRT policy has no significant effect on the randomly selected experimental group, further confirming the robustness and reliability of the research findings.

4.4.2 Exclusion of other policies' effects

The introduction of other policies may also affect urban pollution and carbon reduction levels. Specifically, the low-carbon city pilot policy and the carbon trading policy, implemented around the same period, could potentially affect pollution and carbon reduction. The low-carbon city pilot policy was officially implemented starting July 2010, with following phases launched in November 2012 and January 2017. This policy advocates for industrial restructuring and energy consumption reduction to achieve "dual carbon" objectives and control total carbon emissions. Accordingly, a corresponding policy dummy variable, *DID1*, is established: for demonstration cities, the year of the pilot and following years are set to 1, while other years are set to 0. Besides, in 2011, China initiated the construction of a carbon emissions trading market, designating Shenzhen, Beijing, Shanghai, Tianjin, Guangdong, Hubei, Chongqing, and Fujian as carbon trading pilot regions. Enterprises can buy and sell additional carbon emission rights based on production and operational needs, offering a new pathway for corporate carbon reduction. The policy implementation nodes for this are set in 2011 and 2017, with a corresponding dummy variable, *DID2*, established. The energy-saving and emission reduction measures adopted by the low-carbon city pilot policy and the carbon trading policy have a certain effect on pollution and carbon reduction, suggesting that

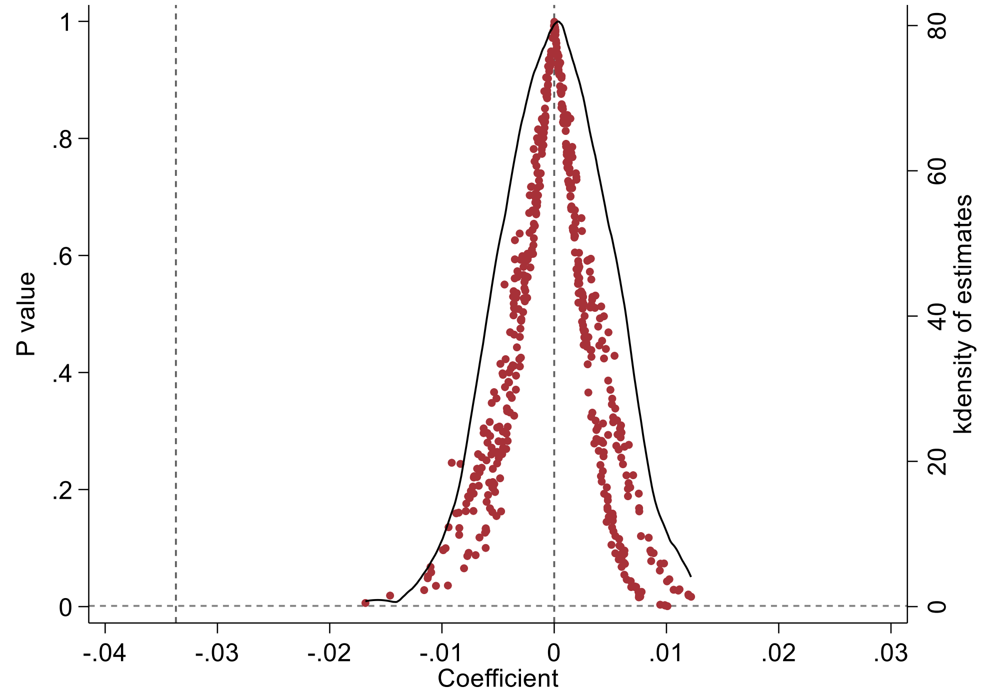

FIGURE 3
Placebo test.

TABLE 4 Robustness test excluding other policies' interference.

Variable	(1)	(2)	(3)
DID	−0.038*** (0.003)	−0.035*** (0.003)	−0.038*** (0.003)
DID1	−0.016*** (0.002)		−0.013*** (0.002)
DID2		−0.016*** (0.003)	−0.007** (0.003)
Con	−0.051** (0.021)	−0.041** (0.021)	−0.057*** (0.021)
Obs	3,480	3,480	3,480
R^2	0.291	0.285	0.292
Controls	YES	YES	YES
Id-fixed	YES	YES	YES
Year-fixed	YES	YES	YES

Note: *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$; robust standard errors are in parentheses.

the effect of the ECRT policy on pollution and carbon reduction levels in pilot areas may have been overestimated.

To eliminate interference from two other policies, dummy variables *DID1* and *DID2* are incorporated into the baseline regression model. The regression results, as presented in Table 4, indicate that both the low-carbon city pilot policy and the carbon trading policy significantly affect urban pollution and carbon reduction levels. Even under these conditions, the regression coefficient of the policy dummy variable for the establishment of the ECRT policy remains significantly negative and virtually unchanged. This finding suggests that the pollution reduction attributed to the ECRT policy has not been overestimated.

4.4.3 Policy exogeneity

The multi-period Difference-in-Differences model requires that the experimental and control groups could not have formed effective expectations prior to the policy implementation, necessitating the assurance of policy exogeneity. Therefore, the regression equation includes a dummy variable for the 3 years prior to the implementation of the ECRT policy (i.e., 2014), with results presented in Table 6. The regression results, after including control variables and controlling for city-fixed effects and year-fixed effects, exhibit that the core explanatory variable's coefficient remains significantly negative, while the coefficient for 2014 is not significant, indicating the absence of anticipatory effects.

4.4.4 Substitution of the explained variable

Following existing literature practices, the baseline regression previously utilized an interaction term of carbon emissions and the environmental pollution index to measure the city's pollution and carbon reduction levels. Industrial sulfur dioxide is also a significant contributor to urban pollution. This paper substitutes industrial sulfur dioxide (*lnso2*) as the dependent variable in the baseline regression for a robustness test, with results demonstrated in Table 5. The inclusion of control variables results in a significantly negative coefficient for the policy dummy variable, further demonstrating the relative robustness of the previous findings.

4.4.5 Exclusion of central cities

The sample data in this study includes 290 cities, including ordinary prefecture-level cities as well as provincial capitals, sub-provincial cities, and municipalities directly under the central government. The behavioral patterns of local governments in

TABLE 5 Other robustness tests.

Variable	Anticipatory Effects Test	Substitution of the Explained Variable	Exclusion of Central Cities
DID	−0.031*** (0.005)	−0.017*** (0.001)	−0.029*** (0.003)
Con	−0.012 (0.020)	0.446*** (0.007)	0.174*** (0.022)
Obs	3,480	3,480	3,480
R^2	0.278	0.087	0.313
Id-fixed	YES	YES	YES
Year-fixed	YES	YES	YES

Note: $^*p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$; robust standard errors are in parentheses.

TABLE 6 Regional heterogeneity test.

Variable	Eastern	Central-Western
DID	0.002 (0.004)	−0.021*** (0.003)
Con	0.022 (0.072)	0.010 (0.117)
Obs	3,480	3,480
R^2	0.870	0.696
Controls	YES	YES
Id-fixed	YES	YES
Year-fixed	YES	YES

Note: $^*p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$; robust standard errors are in parentheses.

TABLE 7 City Level heterogeneity test.

Variable	Core	Ordinary
DID	−0.010*** (0.002)	0.015 (0.015)
Con	−0.043 (0.071)	−0.078 (0.117)
Obs	3,480	3,480
R^2	0.869	0.868
Controls	YES	YES
Id-fixed	YES	YES
Year-fixed	YES	YES

Note: $^*p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$; robust standard errors are in parentheses.

cities of different administrative levels may vary significantly, and higher-level cities control more resources than ordinary cities, potentially leading to biases when regressing all cities together. Therefore, this paper excludes samples from provincial capitals, sub-provincial cities, and municipalities directly under the central government, retaining only ordinary prefecture-level cities for regression. The results, also demonstrated in Table 5, indicate that after excluding central cities, the implementation of the ECRT policy continues to significantly reduce urban pollution intensity and carbon emissions, further verifying the robustness of the aforementioned conclusions.

5 Further tests

5.1 Heterogeneity tests

5.1.1 Regional heterogeneity test

Given the geographical diversity and economic disparities across provinces in China, this study divides the 30 provinces into two sub-samples: Eastern and Central-Western regions. It then conducts regression analyses to assess the effect of the ECRT policy on urban pollution and carbon reduction levels in these regions. The heterogeneity test results, as presented in Table 6, indicate that the policy dummy variable's coefficient is positive and not significant in column 1), but significantly negative in column 2). This indicates that the ECRT policy has a significant effect on reducing carbon dioxide emissions and improving environmental pollution in the Central-Western regions of China, but not in the Eastern regions. This discrepancy can be attributed to the more advanced industrial transformation and ecological management systems in the Eastern regions, which have already achieved success, rendering the effect of the ECRT policy less significant there. In contrast, the Central and Western regions are still in the early stages of industrial transformation, with heavy industry playing a dominant role in their industrial structures. The ongoing severe resource depletion and environmental pollution in these regions make enhancing the ecological environment a pressing issue, hence the more significant policy effects of the ECRT policy.

5.1.2 City level heterogeneity test

The scale and classification of cities might also influence the pollution reduction effects observed in the experimental groups. On one hand, compared to ordinary cities, core cities have significant advantages in terms of industrial structure, government financial input, and transportation levels. These advantages enable core cities to effectively allocate resources through economic agglomeration effects, thereby better addressing environmental pollution issues. On the other hand, core cities carry more functions and have a stronger demand for energy consumption, necessitating the use of significant land resources, which can lead to congestion effects and exacerbate environmental pollution. Therefore, based on the "Notice on Adjusting Urban Scale Division Standards" issued by the Chinese government in 2014, this study categorizes the experimental and control groups into

TABLE 8 Urban resource endowment heterogeneity test.

Variable	Non-Resource-Based	Resource-Based
DID	0.008 (0.007)	−0.039*** (0.002)
Con	0.005 (0.119)	−0.266*** (0.008)
Obs	3,480	3,480
R^2	0.867	0.307
Controls	YES	YES
Id-fixed	YES	YES
Year-fixed	YES	YES

Note: $^*p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$; robust standard errors are in parentheses.

core cities and ordinary cities. Core cities include municipalities directly under the central government, provincial capitals, separately planned cities, and special economic zone cities, while ordinary cities comprise all other cities. The regression results in Table 7 indicate that, compared to ordinary cities, core cities experience a stronger pollution and carbon reduction effect under the ECRT policy. This conclusion suggests that as China continues to establish and optimize its environmental regulatory policies, the governance models of core cities are transforming, which is expected to further alleviate the congestion effects faced during their development.

5.1.3 Urban resource endowment heterogeneity

To explore the differential effects of the ECRT policy on resource-based and non-resource-based cities under varying resource endowments, this study refers to the "National Sustainable Development Plan for Resource-based Cities (2013–2020)" issued by the Chinese government in 2013. Based on the resource endowments of the cities, the 290 cities selected for this study are categorized into 114 resource-based cities and 176 non-resource-based cities. The regression results in Table 8 indicate that the ECRT policy's pilot in resource-based cities has a more significant effect on pollution and carbon reduction. This may be attributed to the relatively homogenous industrial structure of resource-based cities, primarily characterized by labor-intensive and capital-intensive industries with high carbon emissions and pollution levels. The ECRT policy facilitates the flow of innovative elements in resource-based cities, accelerating the transformation and upgrading of industrial structures through the spillover of low-carbon production technologies, thereby promoting industrial low-carbon development and enhancing the capacity for pollution and carbon reduction in these cities.

5.2 Mechanism analysis

Previous results indicate that the ECRT policy significantly reduces urban pollution levels and carbon emissions. The development of the ECRT policy can impact urban pollution and carbon reduction through two channels: upgrading industrial structures and cultivating green technological innovation. Therefore, a transmission effect model is constructed as follows.

Step One: appraise the effect of the implementation of the ECRT policy on the mechanism variables:

$$mech_{it} = \alpha_0 + \alpha_1 did_{it} + \alpha_c X_{it} + \sigma_t + \delta_i + \varepsilon_{it} \tag{7}$$

Step Two: Assess the effect of the mechanism variables on urban pollution and carbon reduction levels:

$$emission_{it} = \beta_0 + \beta_1 mech_{it} + \beta_c X_{it} + \sigma_t + \delta_i + \varepsilon_{it} \tag{8}$$

where $mech_{it}$ represents the mechanism variables, with other variables defined as in Eq. 5. The implementation of the ECRT policy primarily enhances the city's capacity for pollution and carbon reduction by promoting industrial structure upgrading and green technology innovation.

The paper conducts mechanism analysis according to Eqs 7, 8. Table 9 reports the results of the influencing mechanisms of the ECRT policy on urban pollution and carbon reduction levels: The ECRT policy reduces urban pollution levels by promoting industrial structure upgrading and cultivating green technological innovation, thereby optimizing the capacity for pollution and carbon reduction. Hypothesis H2 and H3 are confirmed.

TABLE 9 Mechanism analysis.

Variable	Industrial Structure Upgrading		Green Technology Innovation	
	Ris (1)	Emission (2)	Patent (3)	Emission (4)
DID	0.040*** (0.003)		0.174*** (0.046)	
Ris		−0.050*** (0.012)		
Patent				−0.005*** (0.002)
Obs	3,456	3,456	3,456	3,456
R^2	0.817	0.862	0.799	0.835
Controls	Yes	Yes	Yes	Yes
Id-fixed	Yes	Yes	Yes	Yes
Year-fixed	Yes	Yes	Yes	Yes

Note: $^*p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$; robust standard errors are in parentheses.

6 Discussion

The implementation of the energy use rights trading scheme in China stands as a significant measure taken towards ecological advancement and green development, carrying substantial weight in curtailing energy consumption and emissions, cultivating clean energy development, and propelling economic transformation and upgrading. Studies have demonstrated a significant improvement in pollution and carbon reduction in pilot cities as a direct result of this system, confirming its positive environmental impact. However, research indicates that the improvement in pollution and carbon reduction in these pilot cities only saw a modest increase of 0.034 units, suggesting that the energy use rights trading scheme has not comprehensively enhanced pollution and carbon reduction at the individual prefecture-level city, and its efficacy may not be universally applicable. Several factors could contribute to this limited impact. 1) While China's adoption of an energy use rights trading scheme signals a clear commitment to ecological progress, the system remains in its early stages and has not benefited from the full force of policy and financial backing thus far, which has limited its effectiveness. 2) There appear significant gaps in the supplementary measures and policy support across different pilot regions. For instance, Fujian province has, since 2017, continuously introduced implementation documents for the ECRT policy. These documents have outlined quota allocation plans, providing a legal framework for the scheme. In contrast, the current design of the ECRT policy in Henan province primarily focuses on enterprise compliance, aiming to achieve the province's total energy consumption control targets through market mechanisms, resulting in insufficient market vibrancy. 3) Variations in geographical location, city level, and resource endowment across cities have led to discrepancies in the effectiveness of the energy use rights trading scheme. These gaps could lead to significant differences in the environmental benefits the system brings to different prefecture-level cities.

A mechanistic analysis reveals that cities primarily enhance their level of pollution and carbon reduction through industrial structures upgrading and green technological innovation. Enhanced green technology innovation enables enterprises to implement cleaner production practices, thereby improving urban environmental performance. Moreover, technological innovation represents a fundamental driving force for optimizing and upgrading industrial structures. By optimizing the allocation of energy and resources, industrial structural upgrading can effectively reduce energy consumption.

Heterogeneity analysis reveals that the pollution and carbon reduction levels of cities in central and western China, core cities, and resource-based cities are more significantly influenced by the energy rights trading system. This could be attributed to the fact that eastern regions have relatively mature industrial transformation, upgrading, and ecological environment governance systems, leading to certain achievements. In contrast, central and western regions remain in early phases of industrial transformation and upgrading. The development model dominated by heavy industries still holds a prominent position in their industrial structure, and resource depletion and environmental pollution remain serious concerns. Therefore, the policy effects are more significant in central and western regions. Compared to ordinary cities, core cities possess more comprehensive infrastructure, a more rational industrial layout, and abundant government financial support, providing fertile ground for developing the ECRT policy. On the other hand, ordinary cities have relatively insufficient policy support, and their high-energy-consuming industries are not sensitive to market incentives. Therefore, the impact of the ECRT policy is less significant in ordinary cities compared to core cities. In comparison to non-resource-based cities, resource-based cities in China have richer natural resource endowments but face long-term challenges such as a single industrial structure and high dependence on fossil fuels. The economic development of resource-based cities relies more on resource development and utilization, and related industries often exhibit characteristics of high energy consumption and high emissions, resulting in relatively high energy conservation and emission reduction potential. This renders the ECRT policy more effective in enhancing carbon emission efficiency. The economic development of non-resource-based cities relies more on service industries, manufacturing, and technological innovation. These industries have higher energy utilization efficiency and relatively lower energy conservation and emission reduction potential. However, the ECRT policy can still significantly enhance urban carbon emission efficiency by upgrading industrial structures, cultivating green technology innovation, and facilitating industrial structure upgrading.

In contrast to previous studies (Guo et al., 2023b; Guo et al., 2024c; Feng et al., 2024) that relied on traditional statistical methods, this study leverages panel data from pilot regions to shed lights on the relationship between energy rights trading schemes and urban pollution and carbon reduction initiatives. Addressing the limitations of existing literature (Yang et al., 2023; Hu et al., 2024; Jia et al., 2024; Qiu et al., 2024), this research optimizes the evaluation index system for pollution and carbon reduction at the prefecture-level city. This comprehensive system consists of four key aspects of pollutant emissions: general industrial solid waste generation, carbon dioxide emissions from exhaust gases, total wastewater discharge, and overall carbon emissions.

7 Conclusion and recommendations

This study utilizes panel data including 290 Chinese cities from 2010 to 2021, employing an advanced entropy weight-TOPSIS model to quantify environmental pollution indices. The implementation of the ECRT policy represents a "quasi-natural experiment," with the DID model facilitating empirical analysis. Findings demonstrate that the ECRT policy effectively mitigates urban environmental pollution and carbon emissions. While low-carbon city pilot policies and carbon trading policies also contribute to pollution reduction and decarbonization, robustness tests confirm that the effect of the ECRT policy is not overstated. Heterogeneity studies indicate a more significant effect of the ECRT policy on pollution reduction and emission control in central and western regions compared to the eastern regions. Besides, core cities can leverage the ECRT policy to reduce congestion effects, significantly alleviating pollution emissions. Resource-rich cities, specifically, can enhance the pollution reduction effects of the ECRT policy. Mechanism tests illustrate that the ECRT policy reduces energy intensity, thereby effectively enhancing urban pollution reduction and decarbonization capabilities.

Based on these conclusions, the following policy recommendations are proposed:

Firstly, accelerate the advancement and optimization of China's ECRT market infrastructure. Observations from demonstration cities indicate a synergistic effect of market-incentive-based ECRT policy in reducing carbon emissions and environmental pollutants, achieving coordinated enhancement in pollution reduction and decarbonization. These experiences could be disseminated to other industries and fields, exploring and establishing markets for energy rights, emission rights, and other resource-environmental rights, thereby realizing coordinated governance levels and maximizing environmental management objectives.

Secondly, promote the transformation and upgrading of the energy consumption structure. Mechanism action tests demonstrate that the synergistic effect of the ECRT policy on pollution reduction and decarbonization is driven by cultivating green technological innovation and industrial structure upgrading. Therefore, it is crucial to widely promote green energy-saving emission reduction technologies, clean and efficient processes, and accelerate the transition from traditional to emerging, zero-carbon energies in industrial development. Besides, China needs to expedite the transformation and upgrading of industrial structures, transform traditional high-energy-consuming industries, continuously promote the efficient operation of green industrial projects, and consistently enhance regional green development levels.

Thirdly, coordinated governance of pollution reduction and decarbonization necessitates localization. Empirical results and heterogeneity analysis indicate regional imbalances in China's coordinated governance level of pollution reduction and decarbonization. Environmental pollution management should be tailored to regional economic levels and developmental disparities, exploring locally suitable economic development policies and measures, thereby achieving regional environmental management goals while enhancing coordinated efficiency in pollution reduction and decarbonization.

8 Limitations and future prospects

This study is not without several limitations attributable to data availability and methodological limitations. 1) The findings of this study are based on a Chinese dataset. Future research should explore data sources from other emerging economies to assess the validity and generalizability of these conclusions. 2) This study primarily focuses on the mediating effects of green technology innovation and industrial structure upgrading on the pollution and carbon reduction at the prefecture-level city. However, other potential influencing factors, such as government support and corporate environmental performance, were not included. This might impact the comprehensiveness of the analysis. Future studies should consider incorporating these factors to enrich the current findings. 3) The emissions trading scheme remains in its early phrases of development, resulting in a scarcity of relevant indicators. The effectiveness of emissions trading systems is significantly influenced by market maturity. Future research should study how market forces affect corporate environmental performance and evaluate the impact of the emissions trading market size on urban pollution and carbon reduction efforts.

Data availability statement

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

Author contributions

MW: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Visualization, Writing–original draft, Writing–review and editing. YW: Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Writing–original draft, Writing–review and editing. Ziyi Yang: Data curation, Formal Analysis, Funding acquisition, Methodology, Project administration, Resources, Writing–review and editing. Bingnan Guo: Writing–review and editing, Conceptualization, Project administration, Supervision.

Funding

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

Conflict of interest

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

Publisher's note

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