frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 11 February 2025
DOI 10.3389/fenvs.2025.1455563

OPEN ACCESS

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Lanzhou University, China

*CORRESPONDENCE
Zhaoyang Li,
misiteplant@hhu.edu.cn

RECEIVED 27 June 2024
ACCEPTED 23 January 2025
PUBLISHED 11 February 2025

CITATION
Li Z and Li Y (2025) Evaluation of the impact of the ecological environment damage compensation system on enterprise pollutant emissions.
Front. Environ. Sci. 13:1455563.
doi: 10.3389/fenvs.2025.1455563

Evaluation of the impact of the ecological environment damage compensation system on enterprise pollutant emissions

Zhaoyang Li* and Yisong Li

School of Law, Hohai University, Nanjing, China

The development of an environmental damage compensation framework is a critical innovation in ecological civilization reforms. This study considers the pilot policy for environmental damage compensation reform as a quasi-natural experiment, employing a difference-in-differences approach with emission data from listed companies between 2008 and 2017. The research evaluates the environmental impact of the compensation system's implementation in pilot areas and its implications for improving environmental legal practices. The results show that the compensation system significantly reduces corporate pollution emissions by 1.93% ($p < 0.01$), demonstrating its effectiveness as an environmental governance tool. The heterogeneity analysis reveals stronger effects in heavily polluting industries (3.30%, $p < 0.01$) compared to non-heavily polluting industries (1.25%, $p < 0.1$), in state-owned enterprises (2.06%, $p < 0.01$) versus non-state-owned enterprises (1.71%, $p < 0.1$), and in developed regions (2.50%, $p < 0.01$) compared to underdeveloped areas (1.00%, not significant). The dual mechanisms of negotiation and litigation in the compensation system impose strict constraints on corporate environmental behavior, effectively addressing the issue of "corporate pollution, public suffering, and government expenses." To optimize the system, targeted policy recommendations include strengthening negotiation mechanisms, refining judicial responsibilities, and enhancing coordination in underdeveloped regions. These findings highlight the originality and importance of the compensation framework as a model for balancing ecological protection and economic development.

KEYWORDS

ecological environment damage compensation, environmental governance, pilot policy, DID (difference-in-difference) model, China

1 Introduction

The urgent need to address environmental degradation while maintaining economic development has prompted countries worldwide to explore innovative environmental governance mechanisms. Environmental policies play a vital role in addressing ecological challenges and driving sustainability (Cutcu et al., 2024; Nuta et al., 2024). China, as the world's largest developing country, faces significant challenges in balancing economic growth with environmental protection (Cai and Ye, 2020; Du et al., 2021). In 2015, China initiated a pilot reform of the ecological environment damage compensation system, marking a crucial step in environmental governance reform. This system aims to

address the longstanding issue of "corporate pollution, public suffering, and government expenses" by establishing a comprehensive framework for environmental damage accountability and compensation.

Recent studies have highlighted the complexity of environmental governance and policy effectiveness. Research on carbon neutrality pathways suggests that policy design must consider both economic impacts and environmental benefits (Jiang et al., 2024a). The effectiveness of environmental policies varies significantly across regions due to differences in economic development levels, industrial structures, and institutional capacity (Jiang et al., 2023). Emerging scholarship emphasizes the crucial role of government supervision and attention in environmental performance, with evidence showing that local government engagement significantly enhances green development outcomes through improved regulation and innovation incentives (Hua et al., 2024; Zhang et al., 2024d). Studies on central environmental protection inspections further demonstrate how strengthened oversight can effectively drive emission reductions through both administrative and market mechanisms (Zhang et al., 2024c). Environmental governance research has been enriched by various perspectives, including the role of digitalization in pollution reduction (Yang et al., 2024), spatial coordination of urban agglomerations (Hua et al., 2024), financial growth's spillover effects (Zhang et al., 2024b), and environmental policy innovation diffusion (He et al., 2024). Existing literature has examined various aspects of environmental governance, including market-based instruments (Shao et al., 2023), command-and-control policies (Tang et al., 2020), and hybrid approaches (Chen et al., 2021).

In previous studies, scholars have employed various quantitative methods to assess the impact of environmental policies on corporate behavior. For instance, Earnhart (2004a) utilized panel data analysis to examine how regulatory interventions, such as inspections and enforcement actions, influence the environmental performance of individual polluting facilities. This study incorporated variables like the frequency of inspections and the severity of enforcement actions to evaluate their deterrent effects on non-compliance. Similarly, Zhu et al. (2022) employed a difference-in-differences (DID) approach to investigate the effect of China's new Environmental Protection Law on corporate environmental governance behavior. Their analysis included variables such as environmental investment levels and the presence of central environmental protection inspectors to determine the law's impact on firms' environmental practices. Additionally, Zeng et al. (2022) applied a DID model to evaluate the influence of regional environmental supervision on corporate environmental investment, focusing on the ecological damage compensation system in China. The study considered variables like corporate environmental expenditure and the degree of marketization to assess the policy's effectiveness.

However, several critical gaps remain in our understanding of environmental compensation mechanisms. First, while theoretical frameworks for ecological damage compensation have been extensively discussed (Zhou et al., 2023a), empirical evidence of their effectiveness remains limited. Second, existing studies primarily focus on policy design rather than implementation outcomes (Zhang et al., 2007). Third, the heterogeneous effects of compensation mechanisms across different types of enterprises and regions are largely unexplored (Liu et al., 2021).

This study aims to fill these research gaps by conducting a comprehensive empirical analysis of China's ecological environment damage compensation system. Our research offers several unique contributions. Compared with the existing literature, this study offers several distinctive contributions. First, while prior studies have largely focused on specific environmental policies such as carbon taxes or regulatory enforcement (Earnhart, 2004b; Murray and Rivers, 2015), few have examined ecological compensation mechanisms in a systematic way. Our research addresses this gap by evaluating the impact of China's ecological environment damage compensation system, which represents a comprehensive policy framework targeting corporate pollution behavior. Second, existing empirical studies often lack robust causal identification strategies or focus on cross-sectional analyses (Zhu et al., 2022). By employing a quasi-natural experimental design with a DID methodology, this study provides more reliable evidence of policy effectiveness. Third, this research delves into the heterogeneous impacts of the compensation system across regions and enterprise types, offering nuanced insights into how such mechanisms operate under diverse economic and institutional contexts. Finally, the study's findings have broader implications for global environmental governance, particularly in developing countries, by demonstrating how tailored compensation systems can simultaneously promote corporate environmental responsibility and support sustainable development.

2 Background and hypothesis

2.1 Policy background

The implementation of the 2015 "Pilot Plan" marked the initiation of building an ecological environment damage compensation mechanism at the national level. The core of constructing ecological civilization lies in forming a systematic and comprehensive ecological civilization institutional framework. Introducing the ecological environment damage compensation system strengthens the accountability mechanism, optimizes environmental management, and ecological restoration system, and uses the rule of law to protect the natural environment.

One key factor in the deterioration of environmental issues in China is that enterprises have long been in a state where "the cost of breaking the law is low, and the cost of compliance is high" (Wang et al., 2022), leading to excessive resource consumption and uncontrolled pollution emissions, causing significant environmental damage. Advancing the establishment of an ecological environment damage compensation system seeks to resolve the dilemma of "corporate pollution, public suffering, government paying," thereby fundamentally enhancing environmental governance and restoration. Effective implementation requires exploring and optimizing key issues such as the scope of compensation, determination of responsible parties, clarification of claimants and pathways, damage

identification and assessment, and management of compensation funds. These detailed and systematic aspects aim to build a fair and efficient ecological environment damage compensation system, providing solid institutional guarantees for protecting the natural environment.

2.2 Theoretical hypothesis

The contradiction in local economic development lies in: on one hand, local governments hope to promote industrial chain development through external investment to accelerate economic growth and improve residents' income levels. On the other hand, this industrial expansion often comes with ecological resource consumption and environmental issues, making local governments responsible for managing regional ecological environments (Chen and He, 2023; Wei et al., 2024). Environmental economics suggests that in promoting regional economic growth, the government faces not only ecological resource consumption and the resulting environmental pollution but also the responsibility of restoring damaged ecological environments and improving the supply of ecosystem products and services in the region (Ji and Shin, 2021; Wan, 2024). Enterprises causing environmental pollution should compensate the government for environmental damage. This compensation measure aims to internalize the external costs of ecological protection, clarifying the rights and obligations among different stakeholders. Implementing paid use of resources and promoting the "polluter pays" principle can balance economic development and environmental protection, using economic incentives to encourage government and enterprise cooperation to achieve environmental protection goals (García-Portela, 2023; Zhou et al., 2021).

Legal principles recognize the compensability of ecological services, thus establishing the principle of "the polluter pays," granting specific entities the right to hold environmental damage causers accountable (Malmqvist et al., 2023), achieving ecosystem function restoration and environmental interest protection. The principle of "the polluter pays" is an expression of the principle of equal rights and obligations, emphasizing that environmental damage causers must bear restoration and compensation responsibilities. Many countries follow this principle, setting up similar mechanisms for ecological restoration and compensation (Zhu, 2023). This approach aims to promote ecosystem function restoration and eliminate environmental risks through economic accountability (Safiullah and Kabir, 2024). Studies show that implementing related environmental governance programs effectively enhances local governments' environmental governance enthusiasm and strengthens regional environmental regulatory efforts (Wang et al., 2023; Zhu et al., 2016). Higher environmental governance capabilities and stricter environmental regulation will inevitably inhibit corporate emission behaviors, encouraging companies to achieve energy-saving, emission reduction, and green innovation goals (Xu et al., 2024; Zhang Y. et al., 2024).

Hence, this empirical study proposes the following key hypothesis: The implementation of the ecological environment damage compensation system aids in lowering corporate pollution emissions.

3 Methods

3.1 Data sources

Our study uses a comprehensive dataset covering the period from 2008 to 2017. The corporate pollution emission data are primarily collected from mandatory environmental information disclosures in listed companies' annual reports and Corporate Social Responsibility (CSR) reports. These emission data are further validated through cross-checking with the China Environmental Statistics Yearbook published by the Ministry of Ecology and Environment. The yearbook provides standardized environmental statistics at both provincial and municipal levels, ensuring the reliability and consistency of our pollution measurements. For corporate financial and operational information, we rely on the China Stock Market and Accounting Research (CSMAR) database, which is a widely recognized authoritative database providing standardized financial data for Chinese listed companies. Regional macroeconomic indicators, including GDP *per capita* and industrial structure data, are obtained from the China Statistical Yearbooks published by the National Bureau of Statistics. These yearbooks provide comprehensive economic statistics at both national and provincial levels. After careful data compilation and cleaning process, our final sample consists of 12,440 firm-year observations, covering both pilot and non-pilot regions across China.

The seven pilot regions (Jilin, Jiangsu, Shandong, Hunan, Chongqing, Guizhou, and Yunnan) were selected as the experimental group because they were officially designated as pilot areas for the ecological environment damage compensation system by the central government. This designation reflects comprehensive considerations of regional economic, industrial, and environmental characteristics, ensuring their representativeness. All other non-pilot regions were naturally included as the control group. The division between experimental and control groups thus covers the full scope of the policy's implementation and provides a robust basis for comparative analysis.

Several limitations of our data sources should be noted. First, our sample's focus on listed companies may introduce selection bias, as these companies typically represent larger enterprises with more standardized disclosure practices. Second, although we validate emission data through cross-checking with official statistics, the quality and completeness of environmental information disclosure may vary across firms and years. Third, the statistical yearbook data used for validation and regional indicators have inherent limitations, including reporting lags and potential changes in statistical methodology over time. While these limitations exist, we believe our data validation process and robustness checks help ensure the reliability of our findings.

3.2 Variable settings

The explained variable is corporate pollution emissions (Pollution), with the logarithm of total nitrogen content in sewage selected as the measurement indicator. This selection is

TABLE 1 Variable definition.

Nature	Name	Definition
Explained Variable	Pollution	Logarithm of total nitrogen content in wastewater
Explanatory Variable	Law	Product of Post and Treat
Internal Control Variables	Firm Age	Duration of firm's establishment
	Firm Nature	Coded as 1 if the firm is state-owned, otherwise 0
	Firm Size	Logarithm of total assets
	Firm Revenue	Logarithm of operating revenue
	Firm Profitability	Return on Assets (ROA)
External Control Variables	Economic Development Level	Logarithm of regional per capita GDP
	Industrial Structure	Proportion of GDP from the secondary industry in the region

TABLE 2 Descriptive statistics.

Variable	Sample size	Mean	Standard error	Minimum	Maximum	Skewness	Kurtosis
Firm Pollution Discharge	12,440	7.096	0.265	6.462	7.620	−0.224	2.217
Firm Age	12,440	28.809	3.772	20.000	46.000	0.474	3.332
Firm Nature	12,440	0.635	0.482	0.000	1.000	−0.560	1.313
Firm Size	12,440	22.184	1.477	0.000	28.098	−0.588	12.578
Firm Revenue	12,440	21.512	1.694	9.044	28.689	−0.460	5.241
Firm Profitability	12,440	0.029	0.662	−64.819	20.788	−74.019	7522.377
Economic Development Level	12,440	10.781	0.523	9.085	11.768	−0.330	2.584
Industrial Structure	12,440	45.204	8.992	19.014	61.500	−1.312	4.217

based on several considerations. First, total nitrogen, including ammonia nitrogen, nitrate nitrogen, and nitrite nitrogen, is internationally recognized as a comprehensive indicator reflecting water pollution levels (Houlton et al., 2019). Second, total nitrogen is a more comprehensive indicator than individual nitrogen compounds (such as ammonia or nitrate) because it accounts for all forms of nitrogen pollution and their potential transformations, providing a more accurate assessment of overall water quality degradation (Huang et al., 2017). Third, this indicator has been widely adopted in environmental performance evaluation systems across different countries, making our results internationally comparable (Xu et al., 2009).

The control variables are selected based on established literature in environmental policy evaluation. At the firm level, following Wang et al. (2019), we include firm nature, age, size, revenue, and profitability as these factors significantly influence enterprises' environmental behavior and pollution control capabilities. Specifically, firm nature affects environmental governance willingness and capacity; firm age reflects accumulated environmental management experience; firm size and revenue indicate pollution control resource availability; and profitability shows financial capacity for environmental investment.

At the regional level, based on Zhang et al. (2020), we incorporate economic development level and industrial structure as these macro factors shape the overall context of environmental governance. The economic development level, measured by regional per capita GDP, affects environmental governance investments and technological adoption. Industrial structure, represented by the proportion of secondary industry in GDP, reflects regional pollution emission patterns and environmental pressure.

Tables 1, 2 present the detailed settings and descriptive statistics of the variables, respectively, providing a comprehensive foundation for the subsequent empirical analysis.

3.3 Research design

3.3.1 DID model construction

We employ the DID method to evaluate the impact of the ecological environment damage compensation system for several important reasons. First, this method effectively addresses the endogeneity concerns that commonly arise in policy evaluation studies. By comparing the changes in pollution emissions between pilot and non-pilot regions before and after the policy implementation, DID method helps eliminate the influence of unobservable factors that might affect corporate environmental behavior. Second, the staged implementation of the pilot policy creates an ideal quasi-natural experimental setting, where the selection of pilot regions was determined by the central government based on comprehensive considerations rather than

regions' pollution levels or corporate characteristics. This implementation feature helps mitigate potential selection bias. Third, DID method can effectively control for both time-invariant heterogeneity across regions and common time trends affecting all regions, thereby isolating the true policy effect from other confounding factors.

While various methods can be employed for policy evaluation, the DID approach is particularly well-suited to this study for several reasons. First, unlike propensity score matching (PSM), which primarily addresses selection bias by creating matched samples, DID inherently controls for unobserved, time-invariant heterogeneity between treatment and control groups. Second, while instrumental variable (IV) methods can address endogeneity concerns, they rely on finding valid instruments, which are often challenging to identify in the context of large-scale policy interventions. In contrast, the staged implementation of the ecological environment damage compensation system provides a quasi-natural experimental setting ideal for applying DID. This approach allows us to isolate the policy effect by leveraging the parallel trends assumption, further supported by robustness checks. Therefore, the DID framework offers the most robust and reliable approach for achieving the study's objectives.

Based on the pilot implementation regions, the study sample is divided into two groups: the samples from the seven pilot provinces and cities of Jilin, Jiangsu, Shandong, Hunan, Chongqing, Guizhou, and Yunnan are the experimental group (treat = 1), and the samples from other provinces are the control group (treat = 0). At the same time, 2016 is set as the impact year of the pilot policy, with 2008–2015 as the pre-policy period (post = 0) and 2016–2017 as the post-policy period (post = 1). The study sets up a classic DID model as follows:

$$Pollution_{it} = \beta_0 + \beta_1 post + \beta_2 treat + \beta_3 Law_{it} + \beta_4 Control_{it} + \gamma_t + \mu_i + \delta_{ind} + \varepsilon_{it}$$

where i and t represent companies and time respectively, $Pollution_{it}$ is the explained variable corporate water pollution emissions in this study; Law_{it} is the explanatory variable, represented by the product of $Post_{it}$ and $Treat_{it}$; $Control_{it}$ represents a series of control variables, including corporate nature, age, assets, size, profitability, economic development level, and industrial structure; γ_t represents time fixed effects; μ_i represents individual fixed effects; δ_{ind} represents industry fixed effects, and ε_{it} represents the random error term.

3.3.2 Parallel trend test

The parallel trend test is a critical prerequisite for validating the DID approach. This test ensures that, in the absence of policy intervention, the treatment and control groups would have exhibited similar trends in the outcome variable over time, thereby strengthening the credibility of attributing post-intervention changes to the treatment effect. In this study, the parallel trend assumption is tested using data from 2008 to 2015 as the pre-policy period, with 2016 marking the start of the policy implementation.

To verify the parallel trend assumption, the study uses a combination of graphical and statistical methods. First, the mean pollution emission levels for the treatment and control groups are calculated and plotted over time to provide a visual inspection of their trends before the policy intervention. Second, a series of pre-policy estimates is computed to formally evaluate year-by-year differences in trends between the two groups, using 2015 as the reference year. These estimates are designed to test whether any systematic differences existed prior to the implementation of the ecological damage compensation system reform. By plotting these differences and examining their statistical significance, the parallel trend assumption can be validated.

3.3.3 Placebo test

The placebo test is a critical method for assessing the robustness of the DID analysis. It involves creating hypothetical scenarios by randomly assigning treatment and control groups that do not correspond to the actual policy intervention. This process tests whether the observed effects in the main analysis are driven by random factors, model misspecifications, or biases in the data, rather than reflecting a genuine causal relationship. If significant effects are observed in these placebo scenarios, it raises concerns about the validity of the original results.

In this study, placebo tests are conducted by repeatedly and randomly reassigning treatment and control group labels across the sample. For each random reassignment, a DID analysis is performed under the assumption of a non-existent policy intervention, and the estimated coefficients are recorded. This process generates a distribution of placebo estimates, allowing for the evaluation of whether the observed effects in the main analysis are likely due to random chance.

To enhance the reliability and statistical power of the placebo test, the randomization process is repeated 500 times. By increasing the number of iterations, the distribution of placebo estimates becomes more stable and representative, reducing the likelihood of outlier-driven results. These iterations help to establish a baseline of what the estimated coefficients would look like in the absence of a true intervention. If the original DID estimates fall outside the distribution of placebo estimates, it provides stronger evidence that the observed effects are not due to random variation or omitted variables.

3.3.4 Heterogeneity analysis

Heterogeneity analysis is employed in this study to explore the differential impacts of the ecological environment damage compensation policy across various subgroups. This analysis aims to identify how specific characteristics of firms or regions influence their responses to the policy, providing insights into the diversity of outcomes and the underlying mechanisms of policy effectiveness.

The study examines heterogeneity in three dimensions: industry type, corporate ownership, and regional economic development level. First, firms are categorized into heavily polluting and non-heavily polluting industries based on their primary business activities, as these groups are expected to exhibit different sensitivities to environmental regulations. Second, firms are divided into state-owned enterprises (SOEs) and non-state-owned enterprises (non-SOEs) to assess whether ownership structure influences the effectiveness of the policy. Third, regional economic development levels are considered by grouping firms located in developed and underdeveloped regions, reflecting variations in regional environmental governance capacity and economic priorities.

To conduct the heterogeneity analysis, interaction terms are introduced into the DID framework to capture the varying effects of the policy across subgroups. Separate regressions are also performed for each subgroup, controlling for individual, time, and industry fixed effects to account for unobserved heterogeneity. This approach ensures that the estimated coefficients reflect the differential impacts of the policy while isolating the effects of subgroup characteristics. By comparing the estimated coefficients across subgroups, the study evaluates how the policy's impact varies depending on firm-level or regional factors.

3.3.5 Mechanism analysis

This study employs a case-based approach to examine the mechanisms through which the ecological environment damage compensation system operates. Two representative cases, the Guizhou and Chongqing cases, were selected for their relevance to the research objectives and their ability to illustrate the system's two primary pathways: negotiation and litigation. These cases represent common scenarios of corporate environmental violations in China and provide valuable insights into the policy's implementation.

The Guizhou case involves the illegal dumping of waste gypsum residues by two companies, causing ecological damage to approximately 100 acres of land. The Guizhou Provincial Environmental Protection Department initiated negotiations with the responsible enterprises, seeking a resolution through voluntary agreement. The case highlights how administrative agencies interact with enterprises to address ecological damage.

The Chongqing case centers on excessive wastewater discharge under a third-party governance arrangement. Prolonged pipe leakage resulted in untreated wastewater contaminating the surrounding environment. Attempts to resolve the issue through administrative measures failed, leading to a public-interest lawsuit initiated by the local government and a volunteer organization. The court's ruling clarified liability and enforced joint financial responsibility for ecological restoration.

Data for the analysis were collected from multiple sources, including administrative records, court rulings, and government reports. These were supplemented by secondary analyses from academic literature, media reports, and official policy documents. Together, these sources provide comprehensive information on the environmental damage, the roles of stakeholders, and the outcomes of the compensation mechanisms.

The analysis framework focuses on two mechanisms: negotiation and litigation. The negotiation mechanism examines pre-litigation processes facilitated by administrative agencies, including voluntary agreements and restoration plans. The litigation mechanism explores judicial enforcement in cases where negotiations fail, focusing on court rulings, liability allocation, and compliance outcomes.

The analysis is structured into three steps. First, the cases are contextualized by establishing the environmental and policy background, including the nature of the damage and the roles of key stakeholders. Second, the processes and actions within each mechanism are examined, identifying the interactions between claimants, enterprises, and enforcement bodies. Finally, the effectiveness of the mechanisms is evaluated, focusing on their contributions to pollution reduction and ecological restoration.

Figure 1 illustrates the methodological framework of this study, detailing the key steps and analytical processes involved in the research design.

4 Results

4.1 Basic empirical analysis

Table 3; Figure 2 detail the regression results on how the pilot policy of the ecological environment damage compensation system reform affects corporate pollution emissions. Model (1) shows results without control variables or fixed effects for individuals, time, and industry. Model (2) includes fixed effects for individuals, time, and industry. Model (3) incorporates control variables into Model (1). Model (4) includes both control variables and fixed effects for individuals, time, and industry. Results consistently indicate that the regression coefficients for Law are significantly negative, demonstrating that the pilot policy effectively reduces corporate pollution emissions. As mentioned earlier, the implementation of the ecological environment damage compensation system ensures that the responsible entities bear compensation and restoration obligations, helping to break the "corporate pollution, public suffering, government paying" predicament, which also validates the hypothesis of this study.

4.2 Parallel trend test

Figure 3 visually demonstrates the results of the parallel trend test, a critical step in validating the DID approach. The estimates for the pre-policy period (2008–2015) consistently hover around zero and remain statistically insignificant, as indicated by the overlapping confidence intervals. This confirms that there are no systematic differences in pollution emission trends between pilot and non-pilot regions before the policy implementation, satisfying the parallel trend assumption required for the DID framework.

Post-policy estimates for 2016 and 2017, however, display a significant downward shift, with confidence intervals no longer overlapping with zero. This suggests a noticeable divergence in trends, with pilot regions experiencing a reduction in pollution emissions compared to non-pilot regions following the implementation of the ecological environment damage compensation system. The red vertical line in Figure 3 marks the policy intervention year (2016), clearly delineating the shift in trends before and after the policy.

The results observed in Figure 3 provide strong evidence that the policy-induced changes in pollution emissions can be attributed to the ecological environment damage compensation system, as the pre-policy trends align closely between treatment and control groups while significant differences emerge only after the policy's implementation.

4.3 Placebo test

Figure 4 illustrates the distribution of false DID estimates generated from 500 random groupings of treatment and control

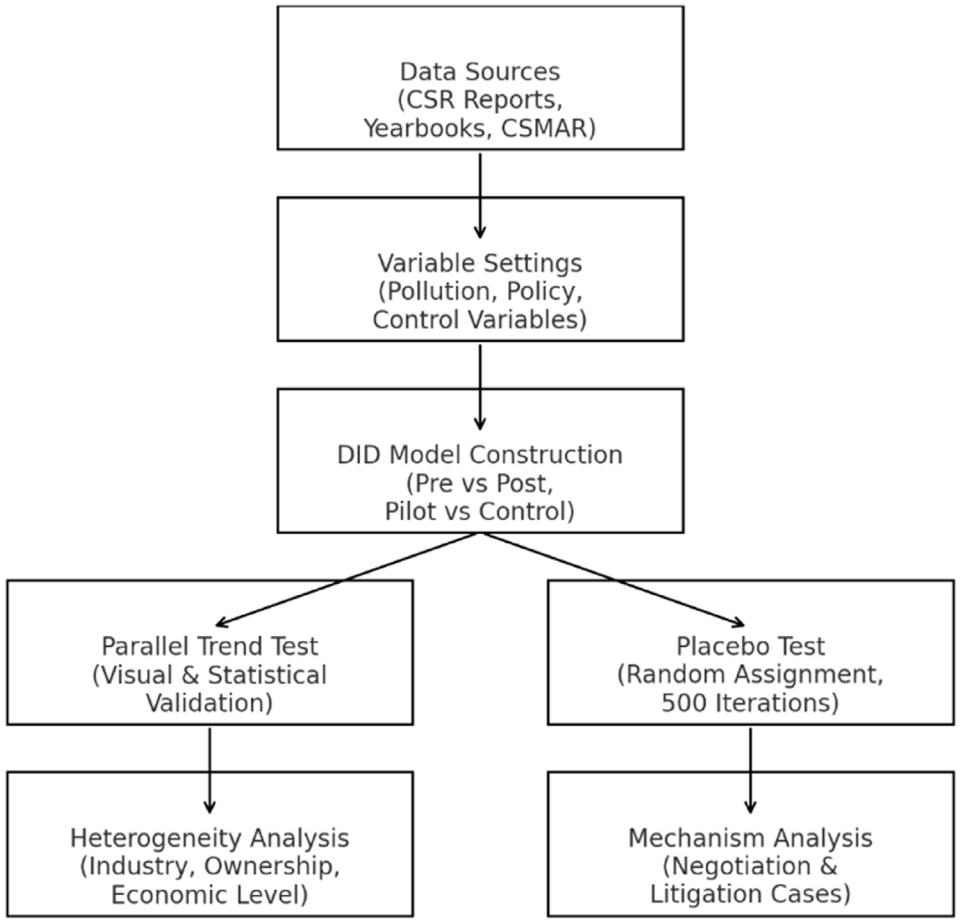

FIGURE 1
Methodology Flowchart.

TABLE 3 Baseline regression.

	(1)	(2)	(3)	(4)
Pollution	Pollution	Pollution	Pollution	Pollution
Law	−0.0182**	−0.0199***	−0.0305***	−0.0193***
	(0.008)	(0.006)	(0.008)	(0.006)
Constant	7.0196***	6.6758***	5.0555***	6.7293***
	(0.003)	(0.005)	(0.051)	(0.114)
Observations	12,440	12,440	12,440	12,440
R-squared	0.323	0.823	0.428	0.823
Control variables	No	No	Yes	Yes
Individual fixed effects	No	Yes	No	Yes
Time fixed effects	No	Yes	No	Yes
Industry fixed effects	No	Yes	No	Yes

***p < 0.01, **p < 0.05, *p < 0.1.

groups. The distribution is centered around zero, with no significant deviations, suggesting that the observed effects in the main analysis are unlikely to result from random assignment or omitted variables. This confirms the robustness of the empirical results and supports the validity of the DID framework employed in this study.

By simulating hypothetical treatment assignments 500 times, the analysis ensures that the significant results observed in the actual treatment-control comparison are not coincidental. The density curve in Figure 4 further highlights the concentration of estimates near zero, demonstrating that the observed effects are distinct from the distribution of false estimates.

Moreover, the lack of extreme values in the placebo distribution indicates that the empirical model adequately controls for potential confounders. This provides additional confidence in the conclusion that the reduction in corporate pollution emissions observed in pilot regions is a result of the ecological environment damage compensation system, rather than random noise or unaccounted-for variables. The placebo test, as shown in Figure 4, thus reinforces the reliability and validity of the study's findings.

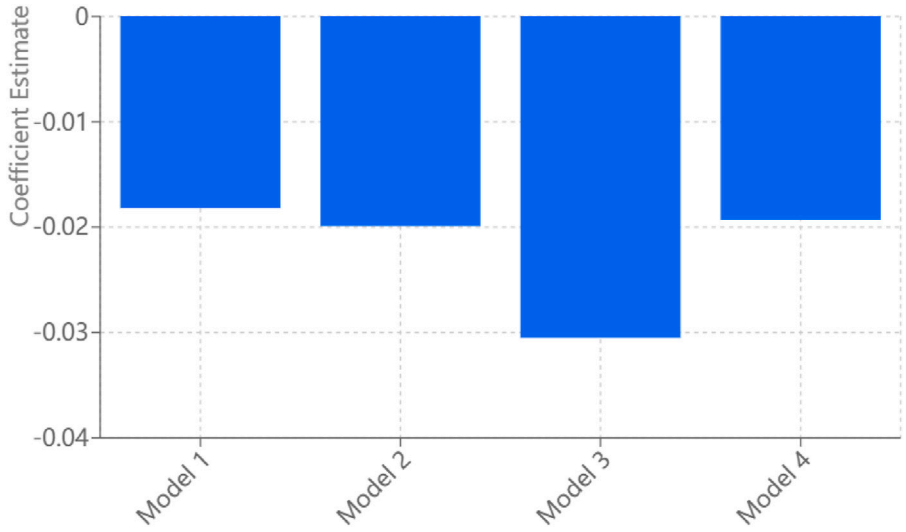

FIGURE 2
Impact of ecological environmental damage compensation system on corporate pollution.

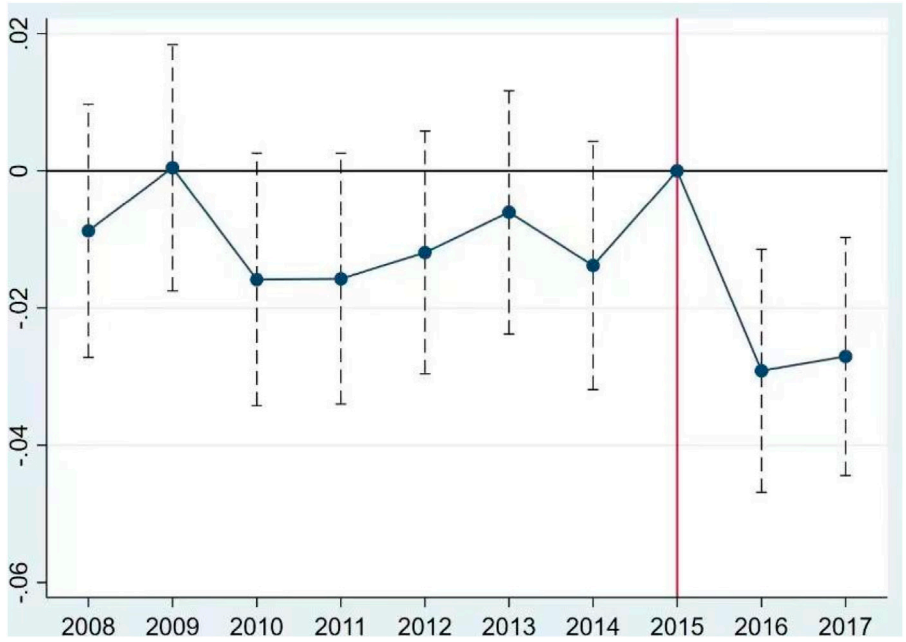

FIGURE 3
Parallel trend test.

4.4 Heterogeneity analysis

Table 4 presents the heterogeneity analysis results, revealing variations in the policy's impact across different subgroups. Models (1) and (2) indicate that the pilot policy has a significantly greater effect on pollution emissions in heavily polluting industries compared to non-heavily polluting industries. This result suggests that heavily polluting industries, with their higher baseline emissions, may have more opportunities for emission reductions under regulatory pressure.

Models (3) and (4) show that state-owned enterprises (SOEs) are more responsive to the pilot policy than non-state-owned enterprises. This difference may reflect the closer alignment of SOEs with government priorities and their better access to resources for implementing environmental measures.

Finally, Models (5) and (6) reveal that the policy's impact is more pronounced in developed regions than in underdeveloped regions. This could be due to the stronger institutional capacity and more advanced environmental governance systems in developed regions, which enhance the implementation and enforcement of the policy.

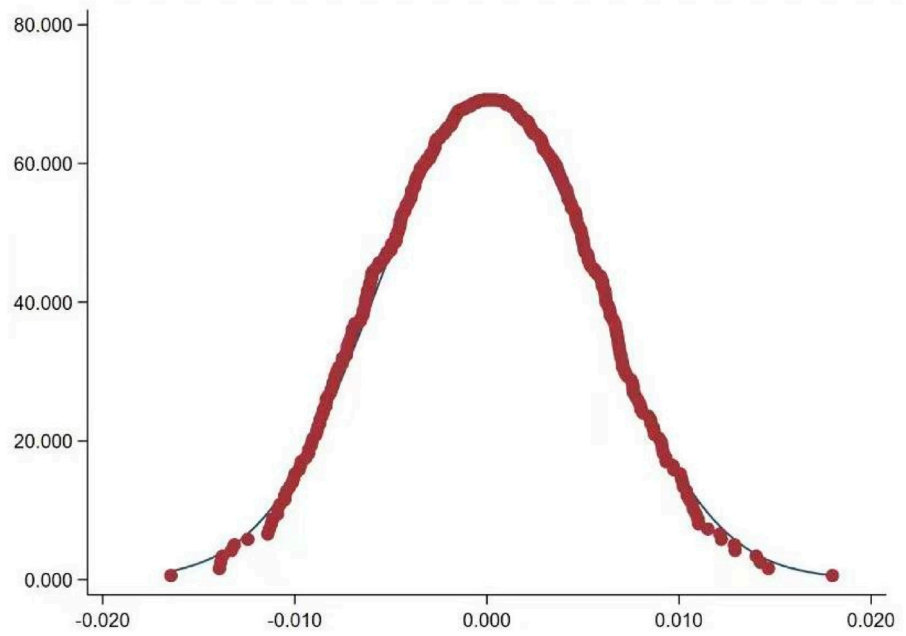

FIGURE 4
Placebo test.

TABLE 4 Heterogeneity analysis.

	(1)	(2)	(3)	(4)	(5)	(6)
	Heavy Pollut	Non-Heavy Pollut	SOE	Non-SOE	Developed	Underdeveloped
Law	−0.0330***	−0.0125*	−0.0206***	−0.0171*	−0.0250***	−0.0100
	(0.012)	(0.007)	(0.008)	(0.010)	(0.008)	(0.011)
Constant	7.1627***	7.0989***	7.0989***	7.1449***	7.2024***	7.1050***
	(0.091)	(0.037)	(0.042)	(0.059)	(0.075)	(0.084)
Observations	2,161	10,250	7,891	4,520	7,507	4,904
R-squared	0.005	0.001	0.002	0.001	0.002	0.001
Individual fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Industry fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

***p < 0.01,**p < 0.05,*p < 0.1.

4.5 Mechanism analysis

The mechanism analysis reveals that the ecological environment damage compensation system achieves pollution reduction through two complementary pathways: the negotiation mechanism and the litigation mechanism.

The negotiation mechanism fosters voluntary cooperation between claimants and enterprises, allowing disputes to be resolved without judicial intervention. This pathway emphasizes flexibility and cost-effectiveness, reducing enterprises' resistance to environmental regulations. For example, in the Guizhou case, the negotiation process led to an agreement where the responsible parties committed to restoring 100 acres of damaged land. The restoration plan included waste removal, land refilling, and vegetation planting, all of which were successfully implemented. This outcome highlights the negotiation mechanism's ability to promote active engagement by enterprises and achieve timely ecological restoration.

The litigation mechanism, by contrast, ensures accountability through judicial enforcement when negotiations fail. This pathway imposes financial and reputational penalties on enterprises, creating a strong deterrent effect against environmental violations. In the Chongqing case, the court imposed joint liability on two

enterprises for restoration costs amounting to 14.416 million yuan. The ruling not only clarified legal responsibilities but also demonstrated the judiciary's role in ensuring compliance. This case illustrates the litigation mechanism's effectiveness in holding enterprises accountable and enforcing ecological restoration measures.

The negotiation and litigation mechanisms work in tandem to address corporate environmental violations. The negotiation mechanism provides a cooperative and flexible pathway for resolving disputes, while the litigation mechanism serves as a robust backup to ensure that non-compliant enterprises face consequences. Together, these mechanisms balance incentives for cooperation with strict enforcement, creating a comprehensive framework that effectively reduces pollution and promotes ecological restoration.

5 Discussion

Compared to traditional command-and-control environmental regulations, this compensation system represents a new type of hybrid policy instrument that combines both administrative and market mechanisms. While environmental tax policies mainly rely on price signals to influence corporate behavior (Liu et al., 2024), and environmental information disclosure policies primarily work through public pressure (Ding et al., 2022), the compensation system creates a more comprehensive incentive structure through both negotiation and litigation channels. This hybrid nature enables the policy to address environmental violations more effectively by providing flexible solutions while maintaining strong deterrence.

The heterogeneous effects we found across ownership types align with previous research on environmental regulation in China. State-owned enterprises show stronger responses to the compensation system, which is consistent with Zhou Z. et al. (2023) findings that state ownership significantly influences enterprises' environmental governance behavior. This difference can be attributed to several factors: state-owned enterprises typically have better access to environmental protection resources, face stronger policy pressure, and are more sensitive to government signals regarding environmental protection.

The regional variation in policy effectiveness revealed in our study supports the theoretical framework of environmental governance capacity. Jin et al. (2016) argue that the effectiveness of environmental policies is closely tied to regional economic development levels, as more developed regions generally have stronger institutional capacity for environmental governance. Our findings provide new empirical evidence for this theoretical perspective, showing that the compensation system works more effectively in developed regions where both administrative and judicial systems are more mature.

The industry-level differences in policy response reveal important insights about environmental policy design. Previous studies have shown that heavily polluting industries typically face more stringent environmental regulations and higher compliance costs (Du et al., 2021). Our results suggest that the compensation system's effectiveness varies across industries, likely due to differences in pollution control capabilities and potential liability risks.

The institutional innovation of the ecological environment damage compensation system also provides new insights into modern environmental governance theory. Traditional environmental regulations often face the challenge of balancing enforcement effectiveness with compliance costs. Our findings suggest that the negotiation-first principle introduced by this system represents a significant advancement in environmental governance approaches. This aligns with recent research by Bodin (2017), who argues that collaborative environmental governance mechanisms can achieve better compliance while reducing administrative costs.

The effectiveness of the dual-track approach combining negotiation and litigation demonstrates the importance of institutional flexibility in environmental governance. Previous studies have shown that rigid environmental regulations may lead to resistance and evasion (Tang et al., 2023). In contrast, the compensation system's flexible negotiation mechanism, backed by strong judicial enforcement, creates a more balanced incentive structure. This finding supports Liao's (2018) argument that environmental policies incorporating multiple governance tools tend to achieve better outcomes than single-instrument approaches.

The success of the ecological compensation system also relates to the broader context of central-local government interactions in environmental governance. As (Jiang et al., 2024b) reveal through case studies, local governments' proactive engagement in environmental policies, rather than passive compliance, tends to achieve better governance outcomes. This finding helps explain why our compensation system shows stronger effects in regions with better institutional capacity.

Our research contributes to the understanding of policy transmission mechanisms in environmental governance. The significant reduction in corporate pollution emissions suggests that the compensation system effectively addresses the "polluter pays" principle implementation challenges identified by Zhu (2023). The system's success in reducing pollution, particularly in heavily polluting industries, indicates that well-designed compensation mechanisms can effectively internalize environmental externalities.

The regional heterogeneity in policy effectiveness revealed by our study also contributes to the broader literature on environmental federalism. In line with recent findings by Chen and He (2023), our results suggest that local institutional capacity significantly influences environmental policy outcomes. This highlights the importance of considering regional differences in environmental governance capacity when designing and implementing national environmental policies.

Furthermore, our findings on ownership-based differences in policy response contribute to the ongoing debate about the role of state ownership in environmental governance. The stronger response observed in state-owned enterprises supports Zhou et al. (2023b) argument that ownership structure significantly influences corporate environmental behavior. This suggests that environmental policies may need to be tailored to account for different ownership structures to maximize effectiveness.

6 Conclusion and policy implications

6.1 Key findings

This study employs a quasi-natural experimental approach to evaluate the impact of China's ecological environment damage compensation system on corporate pollution emissions. Using DID analysis of listed company data from 2008 to 2017, we find that implementing this system significantly reduces corporate pollution emissions by 1.93% ($p < 0.01$). The robustness of these findings is confirmed through parallel trend and placebo tests, demonstrating the policy's effectiveness in addressing environmental challenges.

Our heterogeneity analysis reveals important variations in policy effectiveness across different dimensions. The emission reduction effect is more pronounced in heavily polluting industries (3.30%, $p < 0.01$) compared to non-heavily polluting sectors (1.25%, $p < 0.1$), indicating the system's particular effectiveness in targeting major pollution sources. State-owned enterprises show stronger responses (2.06%, $p < 0.01$) than their non-state counterparts (1.71%, $p < 0.1$), suggesting that ownership structure influences environmental compliance behavior. Additionally, the system demonstrates greater effectiveness in developed regions (2.50%, $p < 0.01$) compared to underdeveloped areas (1.00%, not significant), highlighting the role of regional economic capacity in environmental governance.

The success of this compensation system stems from its innovative dual-track approach combining administrative negotiation with judicial enforcement. Through the "cooperation-negotiation" model, administrative agencies can efficiently achieve ecological restoration and compensation goals. When negotiations fail, the ecological damage compensation litigation system provides robust judicial remedies, imposing strict constraints on corporate environmental violations. This comprehensive framework effectively addresses the longstanding issue of "corporate pollution, public suffering, and government expenses" by creating strong incentives for companies to adopt proactive environmental measures.

6.2 Policy implications

Based on these findings, we propose targeted recommendations for key stakeholders. For government agencies, we suggest strengthening regional coordination mechanisms to address cross-jurisdictional environmental damages, particularly in underdeveloped regions where policy effectiveness is currently limited; standardizing damage assessment procedures and establishing clear guidelines for compensation negotiations; and providing more technical and financial support to local environmental courts to enhance their judicial capacity.

For enterprises, we recommend establishing comprehensive internal environmental risk management systems with regular monitoring and assessment procedures; increasing investment in pollution prevention technologies, especially for heavily polluting industries that showed stronger policy responses; and developing systematic environmental information disclosure mechanisms to improve transparency and accountability.

For environmental organizations, we suggest active participation in ecological damage assessment processes by providing professional expertise and local knowledge; strengthening their role in environmental monitoring and supervision, particularly in regions with weaker institutional capacity; and facilitating communication between government agencies and enterprises during compensation negotiations to promote more effective outcomes.

6.3 Limitations and future directions

Despite these contributions, we acknowledge several limitations of our study. First, the analysis relies primarily on data from listed companies, which may not fully represent the broader corporate landscape, particularly small and medium-sized enterprises. As listed companies typically exhibit better environmental performance and compliance capabilities, our estimates may lean towards conservative results. Second, the relatively short post-policy period (2016–2017) may limit the observation of the long-term effects of the compensation system, as companies may require more time to adjust their environmental practices. Third, while the use of total nitrogen content as a pollution indicator is comprehensive, it does not fully capture all aspects of environmental damage, which could result in an incomplete evaluation of the policy's broader environmental benefits.

Through these findings and limitations, our study contributes to the understanding of environmental governance mechanisms while highlighting areas for future research and policy improvement. The success of the ecological environment damage compensation system suggests that similar approaches could be adapted and implemented in other contexts, particularly in developing countries facing comparable environmental challenges.

Looking ahead, several promising avenues for future research emerge from our study. First, investigating the specific mechanisms through which different types of enterprises respond to environmental policies would provide valuable insights for policy design. Second, examining how local institutional capacity influences policy implementation could help address the regional heterogeneity in policy effectiveness. Third, exploring the interaction between ecological environmental damage compensation systems and other environmental policies could reveal potential synergies in environmental governance. Fourth, conducting comparative studies across different countries could provide broader insights into the adaptability of similar compensation systems in various institutional contexts.

Data availability statement

The datasets presented in this article are not readily available because the processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an

ongoing study. Requests to access the datasets should be directed to Zhaoyang Li, misiteplant@hhu.edu.cn.

Author contributions

ZL: Conceptualization, Data curation, Investigation, Methodology, Software, Writing–original draft, Writing–review and editing. YL: Conceptualization, Funding acquisition, Project administration, Resources, Visualization, Writing–review and editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This research was supported by the National Social Science Fund of China (Grant No. 22BFX131) under the project Legal Protection for the Governance of Transboundary Rivers and Lakes in the Yangtze River Economic Belt, and the Jiangsu Provincial Social Science Foundation Key Project (Grant No. 19FXA002) under the project The Theory and Practice of Local Environmental Legislation.

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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