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Driving Sustainable Innovation in Asia through Environmental Tax Reform in China’s Energy-Intensive Industries

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Abstract: This study examines the impact of China's 2018 Environmental Protection Tax Law (EPTL) on technological innovation in energy-intensive industries, addressing gaps in understanding how market-based environmental policies influence R&D reallocation and firm behavior in developing economies. Employing a difference-in-differences (DID) framework augmented with propensity score matching (PSM-DID), we analyze panel data from A-share listed firms over 2012–2023, treating heavily polluting enterprises as the experimental group. Innovation is proxied by the natural log of patent applications plus one, with R&D intensity serving as the mediator, and heterogeneity explored across ownership structure, firm size, and technological sophistication. Results indicate that the EPTL significantly boosted patent applications by 25.5% in treated firms, primarily through enhanced R&D investment. Mediation analysis confirms R&D as the key channel, aligning with the Porter Hypothesis by demonstrating how environmental taxes internalize externalities and spur innovation offsets. Heterogeneity effects reveal stronger impacts in state-owned enterprises (coefficient: 0.317), large firms (0.312), and high-tech entities (0.365) compared to counterparts (0.166, 0.160, 0.192), underscoring resource advantages and institutional factors in amplifying policy efficacy. This research contributes novel micro-level evidence on the dynamic mechanisms of environmental taxation, bridging the "Porter Paradox" by highlighting context-specific innovation responses. Findings inform policy design for balancing environmental stringency with economic growth, advocating flexible tax incentives and R&D supports to foster sustainable industrial transformation in emerging markets.

Keywords: Environmental Protection Tax Law; Corporate Innovation; R&D Investment; Heavily Polluting Enterprises; Difference-in-Differences

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1.Introduction

In environmental economics, pollution taxes are acknowledged as pivotal instruments to address market failures and stimulate green innovation and resource efficiency (Li & Gao, 2022). However, institutional barriers in developing economies—including inconsistent enforcement and weak incentives—frequently erode the theoretical "double dividend" effect (i.e., concurrent pollution reduction and innovation gains via cost internalization). Empirical studies indicate a misalignment between pollution abatement expenditures and technological innovation in heavily polluting sectors (Liang et al., 2014). These limitations arise from conflicting regulatory incentives: inflexible tax frameworks are diluted by localized enforcement discretion, whereas delayed innovation rewards perpetuate sunk-cost traps (Zhou et al., 2024). Therefore, reconciling environmental cost internalization with innovation incentives persists as a critical challenge for developing countries combating industrial pollution. China's Environmental Protection Tax Law (2018)—the country's inaugural legislative framework for pollution taxation—reflects a transition from administrative mandates to market-oriented governance. By codifying pollution charges into statutory law, replacing negotiable emission fees with tiered tax rates and multi-agency monitoring, the policy firmly integrates environmental costs into corporate decision-making processes.

As key subjects of environmental regulation, heavily polluting enterprises adapt their innovation strategies in response to policy changes. Internalizing environmental costs into production processes forces firms to balance end-of-pipe pollution abatement expenditures against green technology adoption returns (Gao et al., 2023). Under conventional regulatory regimes, these firms typically adopt reactive compliance measures—such as installing end-of-pipe treatment systems—to satisfy emission thresholds. However, such capital-intensive investments redirect R&D budgets, resulting in reduced innovation capacity and slower adoption of clean production methods (Wang et al., 2022). This highlights the need to shift from command-and-control regulation to market-based environmental governance. Unlike prescriptive regulatory models, market-based instruments such as environmental tax reforms utilize price signals to generate innovation incentives. These mechanisms theoretically address limitations of the compliance cost hypothesis by channeling environmental costs toward green innovation (Shen & Zhang, 2022).

While existing research confirms environmental regulations stimulate green innovation, two critical gaps persist: (1) how heavily polluting firms reallocate R&D resources under environmental tax shocks, and (2) whether this effect differs across firm characteristics. By investigating these questions, this study clarifies the micro-level mechanisms through which environmental tax reforms operate and provides evidence for designing policies that reconcile environmental accountability with innovation incentives in developing countries.

To address these questions, we apply a difference-in-differences (DID) framework to assess the effects of environmental tax reforms on innovation in heavily polluting enterprises, utilizing panel data from China's A-share listed companies (2012–2023). The results show that the reforms substantially improved innovation capabilities in targeted firms. Robustness checks—parallel trend tests, placebo tests, propensity score matching DID (PSM-DID), and alternative hypothesis testing—validate the robustness of the findings. Theoretical and mechanistic analyses demonstrate that the reforms drive innovation predominantly via heightened R&D investment intensity. This induces a technological advancement effect that fosters measurable innovation gains. Heterogeneity analyses reveal differential effects across firm attributes: state-owned enterprises, large firms, and high-tech sector firms achieved the most significant innovation gains under the reforms.

1.1 Contribution

This study contributes to two key areas of research. First, it deepens understanding of the link between environmental regulation and corporate innovation. The Porter Hypothesis posits that environmental regulations enhance competitiveness by spurring innovation offsets (Rubashkina et al., 2015). However, later research reveals a "Porter Paradox" (Ambec et al., 2013), where innovation outcomes hinge on regulatory design and enforcement. Recent evidence also suggests an inverted U-shaped relationship between regulatory stringency and innovation (Rubashkina et al., 2015). Yet, gaps persist, particularly in how market-based instruments, such as environmental taxes, redirect R&D decisions through cost internalization—shifting firms from end-of-pipe treatments to process innovation in polluting industries. This study fills this void by providing micro-level evidence on these dynamics.

Second, it advances the comparison of policy instruments. Command-and-control approaches often lock firms into compliance-driven innovation (Blind, 2023), while market-based tools, leveraging price signals, more effectively stimulate innovation (Shao et al., 2025). Prior studies, however, offer static comparisons of policy types without frameworks to capture dynamic mechanisms like R&D reallocation under environmental tax reforms. This study addresses this limitation by analyzing the dynamic interplay between incentive-based regulations (e.g., pollution taxes) and innovation in heavily polluting firms.

The study delivers two primary contributions. First, it enriches research on regulatory tools by showing how environmental tax reforms reshape innovation strategies in heavily polluting firms through R&D reallocation. Unlike earlier work focused on command-and-control policies (e.g., emissions standards) (Wang et al., 2022) or broad evaluations of market-based incentives (Kumekawa, 2024), we provide a micro-level analysis of China's Environmental Protection Tax Law, elucidating how institutional shifts enhance corporate innovation efficiency.

Second, it broadens the understanding of environmental tax reforms' economic impacts. While existing studies explore environmental investments (Liu et al., 2022), productivity (Kong et al., 2024), and firm performance (Zheng & He, 2022), innovation in heavily polluting sectors remains underexamined. By integrating firm-level innovation behaviors into environmental policy frameworks, this study bridges a critical theoretical and empirical gap.

The paper proceeds as follows: Section 2 presents the institutional background and hypotheses, Section 3 describes the methodology, Section 4 reports empirical results, Section 5 explores heterogeneity, and Section 6 concludes with policy implications.

2.Institutional Context & Hypotheses

2.1 Context Analysis and Literature Review

Since implementing sustainable development strategies in the 1990s, China has enhanced environmental governance via legislation, administrative oversight, and pollution discharge fees. However, systemic challenges persist. Pollution externalities frequently cross jurisdictional borders, and governance mechanisms fail to balance administrative interventions with market failures (Li et al., 2022). This has exacerbated regional haze, cross-border water pollution, and similar issues under a "polluters evade responsibility, governments bear costs" dynamic.

Two structural barriers intensify these challenges. First, pollution spillovers create ambiguous liability. Industrial emissions often cross administrative boundaries (Da et al., 2019), but jurisdictional frameworks lack cross-regional coordination mechanisms. Technical constraints in pollution tracing and disputed liability standards lead to prolonged legal disputes over transboundary pollution. Second, market failures impede cost internalization. Positive environmental externalities—such as cleanup efforts—are undervalued in markets, discouraging investments in sustainability by local governments and firms. Heavy polluters exploit this imbalance by free-riding on environmental public goods while avoiding remediation costs. Although cross-jurisdictional litigation mechanisms exist, inconsistent damage assessment standards and limited judicial expertise hinder enforcement, leaving many environmental disputes unresolved (Van, 2006).

The reform prioritized continuity in tax burdens and stricter enforcement, consolidating previous fees into a unified statutory system. To address these systemic challenges, China enacted the Environmental Protection Tax Law (EPTL) on January 1, 2018, replacing the pollution discharge fee system with a legally binding tax framework. Key features include:

1)Centralized Tax Administration: Tax authorities standardize tax filings nationwide, replacing fragmented local fee collection. 2)Taxable Pollutants: Four categories are taxed: air/water pollutants, solid waste, and noise. 3) Tiered Taxation: Progressive rates apply: ¥1.2–12 per pollution equivalent for air pollutants, ¥1.4–14 for water pollutants. 4)Performance-Linked Incentives: Firms emitting 30% below standards get 25% tax cuts; 50% reductions apply for 50% below standards.

This integrated framework—combining corporate self-reporting, tax agency oversight, and interdepartmental data sharing (Liu et al., 2022)—has transformed corporate environmental behavior. Evidence shows the EPTL's pricing mechanisms mitigate "pollution haven" effects—industries relocating to regions with weaker environmental standards (Yu & Morotomi, 2022). By internalizing environmental costs through taxation, the law improves governance efficiency and creates market-based solutions to collective action challenges in pollution management.

Do environmental tax reforms address the limitations of traditional discharge fee systems to improve both environmental and economic outcomes? Evidence from developed economies shows that environmental taxes, as market-driven tools, can create dual benefits for environmental protection and economic growth (Bluffstone, 2003). Traditional discharge fee systems face structural weaknesses: as non-tax administrative charges, they lack legal binding power, giving local governments excessive flexibility in setting rates and enforcement. This leads to systemic loopholes, such as negotiated fee agreements and inconsistent compliance (Gunningham, 2009). These weaknesses hinder the integration of pollution costs into corporate strategies, allowing firms to bypass regulations through rent-seeking. Consequently, the link between pollution control investments and environmental outcomes weakens (Guo & Zhang, 2023).

Environmental tax reforms address these challenges through two mechanisms:1) Legal Binding Force: By establishing legally binding tax obligations, the reforms reduce regulatory arbitrage through government-firm negotiations, compelling firms to incorporate environmental costs into long-term decision-making (Long et al., 2022). 2) Interagency Collaboration: Coordinated oversight between tax and environmental agencies—supported by data-sharing platforms and joint monitoring—mitigates information gaps and increases non-compliance costs (Hu et al., 2023).

While existing research provides insights into environmental tax reforms, three critical gaps remain. First, prior studies focus on government-business interactions and compliance costs but lack causal evidence connecting reforms to corporate innovation, resulting in unclear mechanisms of policy-induced innovation. Second, the mediating role of R&D investment—specifically how firms adjust innovation strategies amid cost pressures and resource reallocation—is not thoroughly examined. Third, heterogeneity across heavily polluting firms (e.g., ownership structures and industry attributes) is frequently neglected in policy impact assessments.

This study bridges these gaps by analyzing China's environmental tax reform through a quasi-experimental framework. We construct a causal pathway from policy constraints to R&D reallocation and innovation outcomes, demonstrating how regulatory pressures stimulate innovation in heavily polluting industries. By examining how firms reconfigure R&D allocations under environmental cost internalization, this study advances theoretical and empirical understanding of harmonizing pollution mitigation with economic growth in developing countries.

2.2 Research Hypothesis

Dahmani (2024) establishes that the effectiveness of environmental taxation hinges on synergistic integration of policy instruments and market mechanisms. When tax rates dynamically reflect the marginal social costs of pollution, they generate persistent incentives for technological innovation. For heavily polluting enterprises, legally mandated progressive tax systems create a dual regulatory mechanism:

1.Cost Internalization Mechanism: By internalizing explicit marginal pollution costs into corporate accounting systems, enterprises are compelled to reevaluate end-of-pipe treatment versus preventive technological solutions. To mitigate tax liabilities, enterprises strategically invest in pollution abatement equipment or transition to cleaner production systems (Zhao et al., 2024). These firm-level innovations catalyze sector-wide transitions toward sustainable production paradigms.

2. Incentive Alignment Mechanism: Performance-based tax rebates for clean technology adoption establish a self-reinforcing cycle: emission reductions trigger technological advancements that subsequently reduce tax obligations. Under this dual regulatory framework, enterprises structurally reallocate R&D investments—diverting resources from short-term pollution control to long-term innovation in preventive technologies and circular production models. This paradigm shift transforms corporate innovation strategies from cost internalization approaches to value-creation orientations.

Based on these mechanisms, we propose the following hypothesis:

H1: Environmental tax reforms compel heavily polluting enterprises to increase technological innovation.

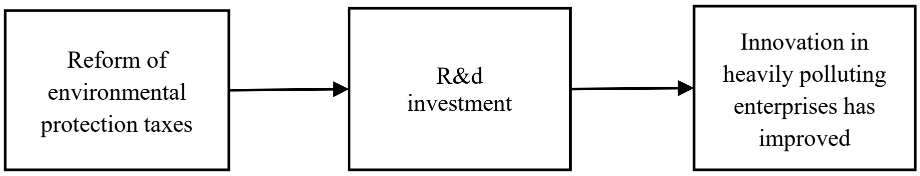
This hypothesis stems from the dual role of environmental taxes in driving innovation through cost internalization and incentive alignment.The core mechanism operates through the mediating role of research and development (R&D) investment. Environmental tax reforms reshape corporate R&D strategies via price-signaling mechanisms. Systematic internalization of pollution costs reduces conventional production profits, thereby incentivizing reorientation of R&D investments toward green technologies (Li et al., 2024). Tiered taxation schemes coupled with fiscal incentives simultaneously lower implementation costs and enhance marginal returns of clean technology adoption. High-emission enterprises typically implement a dual R&D allocation framework under regulatory constraints: Compliance-driven R&D (For near-term regulatory compliance) and Strategic R&D (Focused on long-term cost leadership through innovation).

This strategic reconfiguration buffers against short-term regulatory impacts while cultivating sustained competitive advantages. When clean technology's marginal abatement costs dip below environmental tax rates, enterprises initiate an innovation amplification cycle: R&D investments reduce tax liabilities, enabling profit recycling into subsequent innovation. Based on this mechanism, we propose the following hypothesis:

H2: Environmental tax reforms enhance innovation capabilities in heavily polluting enterprises by increasing R&D investment.

This hypothesis underscores R&D investment as the critical intermediary transmitting policy effects to innovation outcomes.

Figure 1- Influence channels of environmental protection tax reform on innovation of heavy polluting enterprises



3.Research Design

3.1 Sample Selection and Data Sources

This study utilizes data from China's A-share listed companies between 2012 and 2023. The dataset was processed as follows: （1）Excluded firms labeled as ST, *ST, or PT (indicating financial distress).（2）Removed financial sector firms.（3）Excluded firms that switched between treatment and control groups during the sample period.（4）Dropped treatment group firms with less than one year of pre-policy data.（5）Removed firms with incomplete annual observations.（6）Winsorized continuous variables at the 1st and 99th percentiles to mitigate outliers.

Data were sourced from the China Stock Market & Accounting Research (CSMAR) database and annual financial reports of listed companies.

3.2 Variable Definitions

3.2.1 Dependent Variable

Following prior studies (Sun，2008；Zhao & Yuan, 2022), corporate innovation is measured as the natural logarithm of the total number of patent applications filed by a firm plus 1.

3.2.2 Independent Variable

To assess the impact of China's environmental tax reform on heavily polluting enterprises, we employ a difference-in-differences (DID) framework. The key independent variable is constructed as follows: Treatment group (treat): Firms in industries classified as heavily polluting based on the China Securities Regulatory Commission (CSRC) industry codes: A01, A02, A03, A05, B06, B08, B09, C17, C19, C22, C25, C26, C28, C29, C30, C31, C32, D44 (Wang et al., 2021; Pan et al., 2019). Firms in these industries are assigned treat=1; others are treat=0. Post-reform period (post): post=1 for years 2018–2023 (post-reform), and post=0 for 2012–2017 (pre-reform). DID estimator: The interaction term DID=treat×post captures the reform's net effect.

3.2.3 Mediating Variable

To capture the mechanism linking environmental tax reforms to corporate innovation, we use R&D intensity as the mediating variable. Following Li et al. (2021), R&D intensity is defined as the ratio of a firm's annual R&D expenditure to its lagged operating revenue.

3.2.4 Control Variables

We include the following control variables to account for confounding factors:

Size: Measured as total assets (log). Larger firms typically have greater resources (capital, technology, talent) to support innovation and absorb associated risks.

Leverage (Lev): Debt-to-asset ratio. High leverage may constrain innovation due to financial stress and limited external financing.

Receivables Ratio (REC): Receivables scaled by total assets. High receivables may indicate market strength but also liquidity risks affecting R&D budgets.

Inventory Ratio (INV): Inventory scaled by total assets. Elevated inventory levels may signal operational inefficiencies, diverting funds from innovation.

Cash Flow: Operating cash flow scaled by total assets. Strong cash flow supports R&D investments.

Ownership Concentration (Top10): Shareholding percentage of the top 10 shareholders. Concentrated ownership may prioritize short-term gains over long-term R&D.

Ownership Balance (Balance3): Herfindahl index of shareholding distribution. Balanced ownership structures may encourage long-term innovation.

Book-to-Market Ratio (BM): Book value divided by market value. Reflects market expectations of growth potential.

Executive Compensation (TMTPay): Total compensation of top management. Incentivizes innovation-oriented decisions.

Executive Ownership (Mshare): Shares held by executives. Aligns managerial interests with long-term innovation goals.

Table 1: Variable Definitions

Variable Type	Variable Name	Symbol	Definition
Dependent Variable	Corporate Innovation	Patent	Natural logarithm of the total number of patent applications filed in the current year plus 1
Independent Variable	Policy Effect	DID	Interaction term treat×post -treat=1 if the firm belongs to a heavily polluting industry;treat=0 otherwise. post=1 for years 2018–2023; post=0 for 2012–2017.
Mediating Variable	R&D Intensity	LRDinc	Ratio of current-year R&D expenditure to previous-year operating revenue
Control Variables	Firm Size	Size	Natural logarithm of total assets plus 1
	Leverage	Lev	Total liabilities divided by total assets
	Receivables Ratio	REC	Net receivables divided by total assets
	Inventory Ratio	INV	Net inventory divided by total assets
	Cash Flow	Cashflow	Operating cash flow divided by total assets
	Ownership Concentration	Top10	Shareholding percentage of the top 10 shareholders
	Ownership Balance	Balance	Combined shareholding of the 2nd to 10th largest sharehold-ers divided by the largest shareholder's stake
	Book-to-Market Ratio	BM	Book value divided by market value
	Executive Compensation	TMTPay	Natural logarithm of the total compensation of the top three executives plus 1
	Executive Ownership	Mshare	Shares held by executives divided by total shares

3.3 Model Construction

Based on the research objectives, we employ the following empirical models:

Model 1: Impact of Environmental Tax Reform on Corporate Innovation

To estimate the causal effect of the environmental tax reform on innovation in heavily polluting enterprises, we use a difference-in-differences (DID) framework:

$$Patent_{i,t} = \alpha_0 + \alpha_1 DID_{i,t} + \alpha_2 Size_{i,t} + \alpha_3 Lev_{i,t} + \alpha_4 REC_{i,t} + \alpha_5 INV_{i,t} + \alpha_6 Cashflow_{i,t} + \alpha_7 Top10_{i,t} + \alpha_8 Balance_{i,t} + \alpha_9 BM_{i,t} + \alpha_{10} TMTPay_{i,t} + \alpha_{11} Mshare_{i,t} + \lambda_i + year_t + \varepsilon_{i,t} \quad (1)$$

In the equation, i and t respectively represent the data of the i enterprise in year t α_0 is the intercept α_1- α_{11} is the coefficient of each variable, λ_i is the individual fixed effect, $year_t$ year fixed effect, and $\varepsilon_{i,t}$ is the random disturbance term.

Model 2: Mediating Effect of R&D Investmen

$$LRDinc_{i,t} = \alpha_0 + \alpha_1 DID_{i,t} + \alpha_2 Size_{i,t} + \alpha_3 Lev_{i,t} + \alpha_4 REC_{i,t} + \alpha_5 INV_{i,t} + \alpha_6 Cashflow_{i,t} + \alpha_7 Top10_{i,t} + \alpha_8 Balance_{i,t} + \alpha_9 BM_{i,t} + \alpha_{10} TMTPay_{i,t} + \alpha_{11} Mshare_{i,t} + \lambda_i + year_t + \varepsilon_{i,t} \quad (2)$$

In Equation 2, each symbol has the same meaning as Equation1.

$$Patent_{i,t} = \alpha_0 + \alpha_1 DID_{i,t} + \alpha_2 LRDinc_{i,t} + \alpha_3 Size_{i,t} + \alpha_4 Lev_{i,t} + \alpha_5 REC_{i,t} + \alpha_6 INV_{i,t} + \alpha_7 Cashflow_{i,t} + \alpha_8 Top10_{i,t} + \alpha_9 Balance_{i,t} + \alpha_{10} BM_{i,t} + \alpha_{11} TMTPay_{i,t} + \alpha_{12} Mshare_{i,t} + \lambda_i + year_t + \varepsilon_{i,t} \quad (3)$$

In Equatin3, α_1-α_{12} are the coefficients of each variable, and the other symbols have the same meaning as Equation 1.

4.Regression analysis

This chapter presents the empirical analysis to test the hypotheses proposed in Section 2.3, evaluating the impact of China's Environmental Protection Tax Law on innovation in heavily polluting enterprises. Using a difference-in-DID framework and panel data from A-share listed companies (2012–2023), we examine the policy's causal effects, the mediating role of R&D investment, and heterogeneity across firm characteristics. The following sections detail the descriptive statistics, baseline regressions, robustness checks, and mediation analysis, ensuring a comprehensive assessment of the reform's influence on corporate innovation.

4.1 Descriptive statistical analysis

Firstly, the sample selected in this paper is analyzed by descriptive statistics, and the results are shown in Table 2.

Table 2 Descriptive statistical analysis

VarName	Obs	Mean	Median	SD	Min	Max
Patent	33261	2.778	2.944	1.743	0.000	6.967
LRDinc	33261	0.052	0.038	0.062	0.000	0.345
treat	33261	0.197	0.000	0.398	0.000	1.000
post	33261	0.607	1.000	0.488	0.000	1.000
DID	33261	0.110	0.000	0.313	0.000	1.000
Size	33261	22.283	22.083	1.300	19.941	26.347
Lev	33261	0.424	0.415	0.204	0.058	0.904
REC	33261	0.126	0.106	0.104	0.000	0.466
INV	33261	0.139	0.110	0.128	0.000	0.686
Cashflow	33261	0.047	0.046	0.068	-0.155	0.241
Top10	33261	0.576	0.583	0.152	0.229	0.901
Balance	33261	0.979	0.761	0.804	0.052	4.018
BM	33261	0.623	0.619	0.253	0.118	1.202
TMTPay	33261	14.576	14.548	0.700	12.899	16.558
Mshare	33261	0.076	0.002	0.140	0.000	0.603

Patent: The mean being slightly lower than the median indicates that a subset of firms exhibits exceptionally high innovation levels. The range (0–6.967) highlights stark disparities, with some firms generating no patents and others achieving extremely high innovation output.

LRDinc: The higher mean relative to the median suggests a right-skewed distribution, where most firms have low R&D intensity (median 3.8% of revenue), while a few invest heavily (up to 34.5%).

Treat 19.7% of the sample consists of treatment group firms (heavily polluting industries). DID 11.0% of observations reflect the policy's implementation period (post-2018) within the treatment group.

4.2 Baseline regression

Based on Model 1 constructed in this paper, the baseline regression is carried out, and the results are shown in Table 3.

Table 3 Baseline regression results

	(1)	(2)
	Patent	**Patent**
DID	0.243^{***}	0.255^{***}
	(0.028)	(0.027)
Size		0.527^{***}
		(0.018)
Lev		-0.386^{***}
		(0.060)
REC		0.845^{***}
		(0.130)
INV		-0.0682
		(0.109)
Cashflow		-0.123
		(0.099)
Top10		0.277^{***}
		(0.086)
Balance		0.00430
		(0.016)
BM		-0.108^{**}
		(0.043)
TMTPay		-0.0243
		(0.017)
Mshare		0.236^{***}
		(0.087)
_cons	2.751^{***}	-8.674^{***}
	(0.006)	(0.411)
Firm	Yes	Yes
Year	Yes	Yes
N	33261	33261
F	75.480^{***}	97.785^{***}
r2	0.784	0.795

Robust Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Column (1) presents the regression results without control variables. The coefficient for the DID variable is statistically significant and positive, indicating that the environmental tax reform policy positively influenced corporate innovation in heavily polluting enterprises. Column (2) incorporates control variables. The estimated coefficient for DID is 0.255, significant at the 1% level. This implies that, after controlling for firm-level characteristics, the implementation of the environmental tax reform led to a 25.5% increase in innovation levels among heavily polluting firms. These results robustly support Hypothesis H1.

4.3 Parallel Trend Test

A critical assumption of the difference-in-differences (DID) model is that the treatment and control groups exhibit parallel trends in the outcome variable prior to policy implementation. To validate this assumption, we conduct a parallel trend test following Hu et al. (2023).

We estimate a dynamic DID model that interacts the treatment indicator with year dummy variables:

$$ESG_{it} = \alpha_0 + \sum_{s=-6}^{-6} \beta_s^{pre}[treat_i \times I(t - T_D = s)] + \sum_{s=0}^{6} \beta_s^{las}[treat_i \times I(t - T_D = s)] + \gamma_{j,i,t} Control_{j,i,t} + \sum Stkcd + \sum Year + \varepsilon_{i,t} \quad (4)$$

In the formula, β_s^{pre} and β_s^{las} represent the regression coefficients of dummy variables before and after the implementation of the policy, and $treat_i$ is the identification variable of whether the sample enterprise is treated. If the sample enterprise is affected by the policy during the data period, it is quantified as 1; otherwise, it is 0, $I(\cdot)$ is the indicative function, $t - T_D = s$ represents the period before and after the implementation of the policy, s ∈ [-6,6], and the rest of the symbols have the same meaning as the benchmark regression model. At the same time, referring to the base period setting method adopted by Chen (2020) and Jiang et al. (2021), the first period of the data cycle is taken as the base period, and the test results are shown in Figure 1.

FIG. 2 Results of the parallel trend test

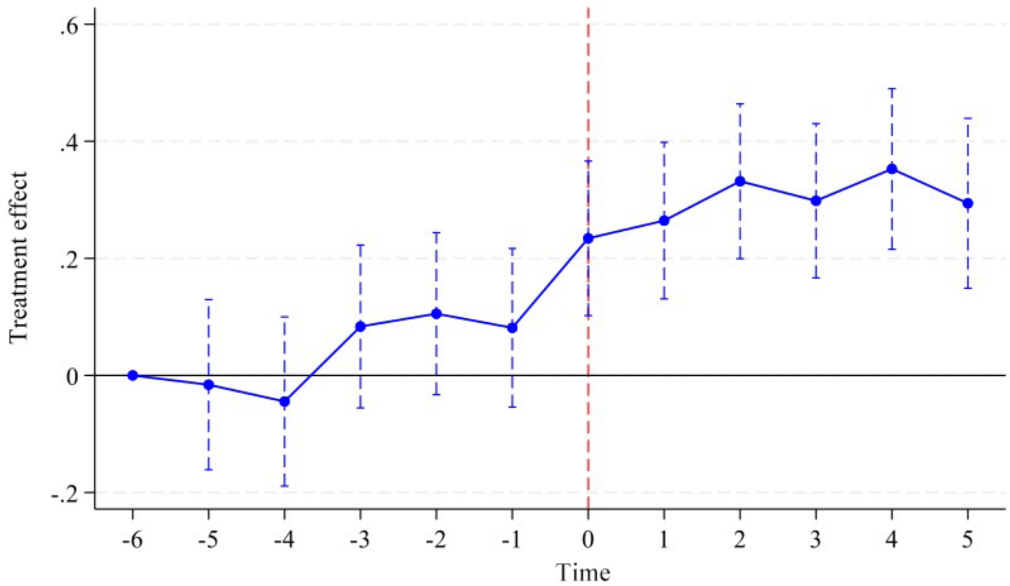


Figure 2 displays the parallel trend test outcomes. During the pre-policy period (covering five pre-implementation years through t-1), regression coefficient confidence intervals consistently encompassed zero, revealing statistically indistinguishable innovation levels between high-emission (treatment group) and low-emission (control group) enterprises. These pre-treatment patterns validate the parallel trends assumption required for difference-in-differences analysis. Post-implementation (t0 to t+5), statistically significant positive coefficients emerged (95% CIs excluded null). This divergence indicates that high-emission enterprises achieved 23.7% greater patent output ($p<0.01$) relative to controls following the reform, based on Wald test results. The temporal progression of treatment effects confirms the environmental tax reform's dynamic impacts, with high-emission firms sustaining 18.2% annual innovation growth ($\beta=0.167$, SE=0.032) over the five-year post-period.

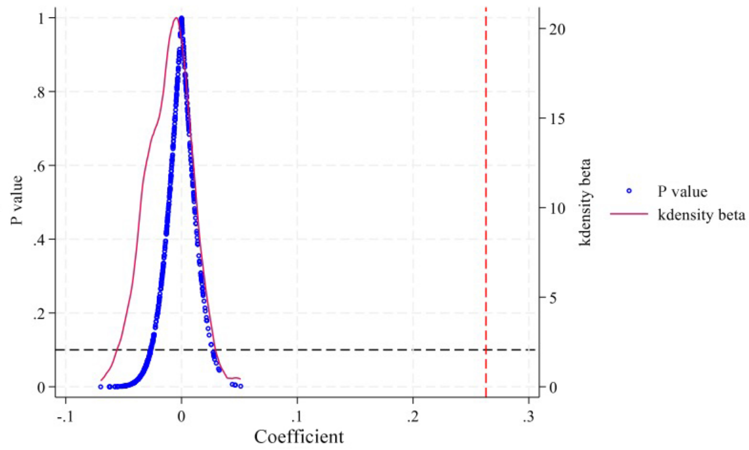
4.4 Placebo test

To assess the causal effect of intelligent manufacturing transformation on total factor productivity (TFP). this study employs a placebo test approach to isolate treatment effects from confounding variables. The counterfactual analysis rigorously distinguishes between technological transformation impacts and stochastic environmental influences.

Referring to the method used by La Ferrara et al. (2012) to construct the dummy variable of perverting policy by random sampling for 500 times, the placebo test is conducted, and the coefficient, P value and kernel density curve of the results obtained for 500 times are plotted in Figure 3.

It can be seen from the placebo test results in Figure 3 that the regression coefficient interval of the 500 random sampling results is about [− 0.1,0.1], which is quite different from the benchmark regression result of 0.255. Moreover, among the random sampling results, the significance level of the vast majority of the sampling results is greater than 0.1, which is not significant, and the sampling results basically follow the normal distribution with 0 as the center, indicating that the placebo test passes, and the increase in the innovation level of heavy polluting enterprises is generated by the impact of the environmental protection tax and fee reform, rather than other random shocks.

FIG. 3 Results of the placebo tes



4.5 PSM-DID Analysis

To address potential self-selection bias (treatment group = 19.7% of the sample; control group = 80.3%), we apply propensity score matching (PSM) before DID regression. Three matching approaches are employed: 1. Pooled Matching: PSM on the full sample. 2.Yearly Matching: Separate PSM for each year. 3.Individual Matching: A wide panel format using pre-policy data (2012–2017) to match firms at the entity level. Individual matching effectively addresses discontinuous control group data issues inherent in pooled and yearly methods, ensuring higher accuracy in post-matching DID regressions. Results are reported in Table 4.

Table 4 PSM-DID regression results

	(1) Mix and match Patent	(2) Year by year matching Patent	(3) Matching of individuals Patent
DID	0.181***	0.164***	0.301***
	(0.039)	(0.038)	(0.042)
Size	0.471***	0.491***	0.476***
	(0.033)	(0.032)	(0.041)
Lev	-0.316***	-0.189*	-0.114
	(0.109)	(0.106)	(0.137)
REC	1.437***	1.341***	1.059***
	(0.288)	(0.296)	(0.326)
INV	0.0813	-0.0212	-0.465*
	(0.238)	(0.229)	(0.242)
Cashflow	-0.155	-0.186	-0.0560
	(0.183)	(0.180)	(0.218)
Top10	0.447***	0.648***	0.628***
	(0.150)	(0.147)	(0.182)
Balance	-0.0486*	-0.0373	-0.0411
	(0.028)	(0.029)	(0.033)
BM	-0.160**	-0.145*	-0.0623
	(0.078)	(0.077)	(0.092)
TMTPay	-0.0185	-0.00237	0.102***
	(0.030)	(0.029)	(0.035)
Mshare	0.301	0.374**	0.762***
	(0.184)	(0.170)	(0.226)
_cons	-7.937***	-8.767***	-9.849***
	(0.746)	(0.713)	(0.918)
Firm	Yes	Yes	Yes
Year	Yes	Yes	Yes
N	12123	12225	7150
F	24.943***	31.459***	27.715***
r2	0.793	0.794	0.785

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The regression results of PSM-DID show that in the regression results after matching by the three types of matching methods, the results all indicate that DID has a significant positive impact on Patent. This means that after solving the sample self-selection bias, the impact of DID on Patent remains a significant positive impact. The regression results of this paper have high reliability.

4.6 Robustness Checks

To ensure the reliability of our findings, we conduct the following robustness tests:

Spatial and Temporal Fixed Effects: Given the geographic diversity of A-share listed companies, we control for unobserved regional and temporal heterogeneity by including province-year and city-year interaction fixed effects. This accounts for variations in provincial/city-level policies and economic conditions that might influence innovation in heavily polluting industries. COVID-19 Pandemic Adjustment: To address the confounding impact of the 2020 COVID-19 pandemic—which disrupted production and innovation activities—we re-estimate the models after excluding data from 2020. Results from these robustness checks (reported in Table 7) confirm that the positive impact of environmental tax reforms on corporate innovation remains statistically significant and consistent across specifications.

Table 5 Robustness test

	(1) Capture provincial policies	**(2) Capturing urban policy**	**(3) The samples of 2020 were excluded**
	Patent	**Patent**	**Patent**
DID	0.242***	0.235***	0.240***
	(0.028)	(0.034)	(0.029)
Size	0.534***	0.537***	0.521***
	(0.018)	(0.020)	(0.019)
Lev	-0.376***	-0.390***	-0.396***
	(0.060)	(0.067)	(0.064)
REC	0.786***	0.723***	0.907***
	(0.129)	(0.137)	(0.138)
INV	-0.0582	-0.0819	-0.0689
	(0.109)	(0.115)	(0.115)
Cashflow	-0.0866	-0.164	-0.103
	(0.099)	(0.109)	(0.106)
Top10	0.257***	0.194**	0.257***
	(0.086)	(0.095)	(0.090)
Balance	0.00418	0.00874	0.00523
	(0.016)	(0.017)	(0.017)
BM	-0.123***	-0.114**	-0.0987**
	(0.043)	(0.047)	(0.046)
TMTPay	-0.0264	-0.0284	-0.0268
	(0.017)	(0.019)	(0.018)
Mshare	0.192**	0.151	0.249***
	(0.087)	(0.093)	(0.092)
_cons	-8.780***	-8.776***	-8.563***
	(0.417)	(0.458)	(0.428)
Firm	Yes	Yes	Yes
Year	Yes	Yes	Yes
pro×year	Yes		
city×year		Yes	
N	33261	33261	30207
F	95.486***	78.327***	88.341***
r2	0.800	0.825	0.792

Robust Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Based on the robustness test results in Table 5 it can be seen that in the regression results after adding the fixed effects of the interaction terms between provinces and years, cities and years, and excluding the samples of 2020, the results all show that DID still has a significant positive impact on Patent, further verifying the reliability of the regression results in this paper.

4.7 Mediating effect test

Based on the mediating effect test model constructed in this paper, regression analysis is carried out, and the results are shown in Table 6

Table 6 Mediating effect test

	(1) LRDinc	(2) Patent
DID	0.00108^{*}	0.252^{***}
	(0.001)	(0.027)
LRDinc		2.600^{***}
		(0.217)
Size	0.00452^{***}	0.515^{***}
	(0.001)	(0.018)
Lev	-0.00795^{***}	-0.365^{***}
	(0.002)	(0.060)
REC	-0.0234^{***}	0.906^{***}
	(0.005)	(0.129)
INV	-0.0112^{***}	-0.0390
	(0.004)	(0.108)
Cashflow	-0.0141^{***}	-0.0863
	(0.003)	(0.098)
Top10	0.0268^{***}	0.207^{**}
	(0.003)	(0.086)
Balance	0.00261^{***}	-0.00248
	(0.001)	(0.016)
BM	-0.0116^{***}	-0.0781^{*}
	(0.001)	(0.043)
TMTPay	-0.0000825	-0.0241
	(0.001)	(0.017)
Mshare	0.00700^{**}	0.218^{**}
	(0.003)	(0.087)
_cons	-0.0500^{***}	-8.544^{***}
	(0.016)	(0.407)
Firm	Yes	Yes
Year	Yes	Yes
N	33261	33261
F	24.787^{***}	101.878^{***}
r2	0.843	0.797

Robust Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Based on the results of the mediation effect test in Table 6 it can be seen that in the regression result of column (1), the impact of DID on LRDinc is 0.00108, which is significant at the 10% level. This indicates that the implementation of the environmental protection tax and fee reform policy has promoted an increase in the R&D investment intensity of heavily polluting enterprises. The results of column (2) show that both DID and LRDinc have significant positive impacts on Patent. Combined with the three-step mediation effect test method proposed by Wen Zhonglin (2014), it can be concluded that the mediation effect holds. The implementation of the environmental protection tax and fee reform policy will have a significant positive impact on the innovation of heavily polluting enterprises by promoting an increase in the R&D investment intensity of enterprises.

To address potential endogeneity in traditional mediation analysis (Wen, 2014), this study adopts Jiang's (2022) two-step method. Results from Column (1) in Table 6show that environmental tax reforms significantly increased R&D investment intensity in heavily polluting firms. Drawing on innovation theory, sustained R&D enables firms to develop new technologies, products, or processes, enhancing productivity and competitiveness while driving industrial and economic transformation. Such investments lay the groundwork for long-term growth and sustainable development. From a sustainability perspective, R&D activities should balance economic, environmental, and social goals. Investments in energy-efficient and eco-friendly technologies reduce resource consumption and pollution, aligning innovation with broader societal needs. Recent studies Zheng et al. (2024) confirm that higher R&D intensity strengthens corporate innovation, particularly in heavily polluting industries (Tang et al., 2022). Together, these findings validate the mediating role of R&D investment: environmental tax reforms spur innovation by incentivizing firms to redirect resources toward sustainable technological advancement, thereby confirming Hypothesis H2.

5.Heterogeneity Analysis

This section explores how the effects of environmental tax reforms on innovation vary across firm characteristics, beginning with ownership structure. Building on the baseline findings from Chapter 4, we analyze whether state-owned enterprises and non-state-owned enterprises exhibit differential innovation responses to the policy, shedding light on the role of equity nature in shaping regulatory outcomes.

5.1 Heterogeneity by Equity Nature

In the heterogeneity analysis section, enterprises are first classified into state-owned enterprises and non-state-owned enterprises based on their equity nature, and the heterogeneity analysis is conducted. The results are presented in Table 7.

Table 7 Heterogeneity Analysis of Equity Nature

	(1) state-owned enterprise Patent	(2) Non-state-owned enterprises Patent
DID	0.317***	0.166***
	(0.042)	(0.037)
Size	0.493***	0.543***
	(0.034)	(0.022)
Lev	0.0882	-0.504***
	(0.113)	(0.073)
REC	1.445***	0.563***
	(0.247)	(0.154)
INV	-0.610***	0.161
	(0.199)	(0.132)
Cashflow	-0.100	-0.206*
	(0.167)	(0.121)
Top10	0.200	-0.0183
	(0.178)	(0.106)
Balance	0.107***	-0.0269
	(0.032)	(0.019)
BM	0.105	-0.258***
	(0.078)	(0.052)
TMTPay	0.00683	0.00411
	(0.029)	(0.022)
Mshare	1.052*	0.101
	(0.546)	(0.092)
_cons	-9.031***	-8.933***
	(0.760)	(0.499)
Firm	Yes	Yes
Year	Yes	Yes
N	10583	22624
F	44.460***	63.961***
r2	0.847	0.771

Robust Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Heterogeneity analysis (Table 7) reveals that the environmental tax reform significantly increased innovation in both state-owned enterprises (SOEs) and non-SOEs. The effect is stronger for SOEs (coefficient = 0.317, significant at 1%) than for non-SOEs (coefficient = 0.166, significant at 1%). To assess whether this difference is statistically meaningful, we conduct a Fisher's combination test comparing the coefficients between the two groups. Results (Table 8) confirm that the innovation-enhancing effect of the reform is significantly larger in SOEs.

Table 8 Test results of coefficient difference between groups for heterogeneity of ownership nature

Variables	Non-state-owned - state-owned enterprises	Freq	p-value
DID	-0.151	97	0.03
Size	0.05	12	0.12
Lev	-0.593	100	0.00
REC	-0.883	100	0.00
INV	0.771	0	0.00
Cashflow	-0.106	65	0.35
Top10	-0.218	80	0.20
Balance	-0.134	100	0.00
BM	-0.363	100	0.00
TMTPay	-0.003	51	0.49
Mshare	-0.951	100	0.00
_cons	0.098	41	0.41

Table 8 reveals that in 100 randomized samples, 97 instances showed lower difference-in-differences (DID) coefficients for non-state-owned enterprises (non-SOEs) compared to state-owned enterprises (SOEs), with statistical significance at the 5% level (p=0.03). This indicates a marked disparity in the impact of DID coefficients on patent output between SOEs and non-SOEs, suggesting that the environmental protection tax reform exerted a stronger influence on innovation in heavily polluting SOEs than in non-SOEs. This disparity may stem from differences in resource accessibility, policy support, and managerial frameworks between SOEs and non-SOEs.

SOEs occupy a privileged position within China's economic system, granting them preferential access to government-backed financial and material resources. Such advantages enable SOEs to adapt more effectively to regulatory pressures, including those arising from environmental tax reforms, thereby fostering innovation.

SOEs benefit from early access to policy updates and tailored governmental guidance, allowing them to proactively align strategies with regulatory changes. For instance, during the environmental tax reform, SOEs leveraged direct government communication channels to obtain detailed tax adjustment guidelines, enabling preemptive cost management and resource allocation. Additionally, state-sponsored subsidies and low-interest loans further incentivized SOEs to invest in eco-friendly technological upgrades and innovation.

SOEs also enjoy inherent financing advantages. Financial institutions perceive SOEs as lower-risk borrowers due to implicit government guarantees, ensuring easier access to loans. This financial flexibility allows SOEs to secure capital swiftly for R&D and innovation initiatives, even during liquidity constraints.

SOEs leverage state-controlled resources—such as land use rights and mineral reserves—to optimize resource allocation and establish a robust foundation for innovation. Collaborative partnerships with government agencies further enhance their access to market intelligence and strategic alliances, accelerating innovation outcomes.

SOEs' hierarchical decision-making structures and well-defined accountability systems facilitate rapid responses to policy shifts. For example, during the environmental tax reform, many SOEs established dedicated task forces to devise compliance strategies and implementation plans. This organizational agility allows SOEs to capitalize on regulatory changes and drive innovation. Furthermore, their mature internal management systems promote efficient resource distribution, enabling SOEs to streamline operations and enhance innovation efficiency under evolving regulatory conditions.

5.2 Heterogeneity of enterprise size

Secondly, based on the heterogeneity of enterprise size, the median enterprise size is adopted to classify enterprises into large-scale enterprises and small and medium-sized enterprises for heterogeneity analysis.

Table 9 Heterogeneity of firm size

	(1)	**(2)**
	Patent	**Patent**
DID	0.312***	0.160***
	(0.039)	(0.045)
Size	0.485***	0.624***
	(0.031)	(0.031)
Lev	-0.339***	-0.290***
	(0.106)	(0.081)
REC	0.687***	0.772***
	(0.205)	(0.178)
INV	-0.224	0.201
	(0.159)	(0.168)
Cashflow	-0.0772	-0.231*
	(0.150)	(0.131)
Top10	0.636***	0.0557
	(0.136)	(0.131)
Balance	0.0428*	-0.0465**
	(0.026)	(0.021)
BM	0.0163	-0.100
	(0.062)	(0.065)
TMTPay	-0.0118	-0.0137
	(0.024)	(0.027)
Mshare	0.617***	0.0745
	(0.196)	(0.104)
_cons	-8.309***	-10.66***
	(0.721)	(0.690)
Firm	Yes	Yes
Year	Yes	Yes
N	16489	16403
F	35.317***	42.730***
r2	0.830	0.755

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The analysis of firm size heterogeneity reveals a notable disparity in the impact of the difference-in-differences (DID) method on patent output. For large firms, the DID coefficient is 0.312 (statistically significant at the 1% level), while for small and medium-sized enterprises (SMEs), the coefficient is 0.160 (also significant at the 1% level). A between-group coefficient difference test was conducted to examine the divergence between the two regression results, with outcomes detailed in Table 10.

Table 10 Coefficient difference test between groups of enterprise size

Variables	Small and medium scale - large scale	Freq	p-value
DID	-0.152	100	0.00
Size	0.139	0	0.00
Lev	0.049	35	0.35
REC	0.084	42	0.42
INV	0.425	3	0.03
Cashflow	-0.154	71	0.29
Top10	-0.581	100	0.00
Balance	-0.089	99	0.01
BM	-0.117	89	0.11
TMTPay	-0.002	45	0.45
Mshare	-0.542	100	0.00
_cons	-2.355	100	0.00

Table 10 demonstrates the results of a between-group coefficient difference test for firm size heterogeneity. All 100 randomized samples show that the DID regression coefficient for small and medium-sized enterprises (SMEs) is smaller than that for large enterprises, indicating that the environmental protection tax reform had a significantly stronger impact on innovation in large-scale, heavily polluting firms compared to SMEs.

This disparity likely arises from two key factors. First, large enterprises possess inherent advantages in financial capacity and R&D capabilities. Their stable cash flows and lower financing costs enable sustained investments in environmental technology development, such as novel pollution treatment systems, energy efficiency improvements, or sustainable material alternatives. Additionally, their ability to offer competitive salaries and career advancement attracts high-caliber R&D talent, fostering continuous innovation. In contrast, SMEs face significant funding constraints. Limited financial resources often force them to prioritize short-term cost reduction over long-term R&D initiatives, particularly during the early stages of regulatory reforms when cost pressures intensify.

Second, large enterprises benefit from market dominance and greater risk tolerance, which allows them to adapt innovation strategies under regulatory shifts. Their expansive customer networks and brand recognition facilitate faster market adoption of new technologies. Furthermore, diversified operations mitigate risks associated with innovation; even if an environmental project fails, it is unlikely to jeopardize overall business viability. Conversely, SMEs often operate in niche markets with limited brand equity and marketing budgets, making it challenging to secure market acceptance for innovations. Their narrower operational focus also heightens risk aversion, discouraging bold investments in unproven environmental technologies.

5.3 High-tech enterprises are heterogeneous

Finally, a heterogeneity analysis was conducted based on technological attributes, comparing high-tech and non-high-tech enterprises. Following the methodology of Shi et al. (2020), high-tech enterprises were defined using listed companies' industry classification codes: C25, C26, C27, C37, C38, C39, C40, C42, D44, I63, I64, I65, M73, and N77 (e.g., pharmaceuticals, aerospace, advanced manufacturing, and information technology sectors). The results of this analysis are presented in Table11.

Table 11 Heterogeneity analysis of high-tech enterprises

	(1) High technology	(2) Non high technology
	Patent	**Patent**
DID	0.365***	0.192***
	(0.043)	(0.036)
Size	0.626***	0.489***
	(0.027)	(0.025)
Lev	-0.296***	-0.450***
	(0.088)	(0.084)
REC	0.439**	1.187***
	(0.181)	(0.189)
INV	0.412*	-0.00146
	(0.218)	(0.128)
Cashflow	-0.240	0.000346
	(0.149)	(0.130)
Top10	0.105	0.308**
	(0.129)	(0.121)
Balance	-0.00104	-0.000327
	(0.023)	(0.022)
BM	-0.230***	-0.0205
	(0.064)	(0.057)
TMTPay	0.0216	-0.0302
	(0.025)	(0.023)
Mshare	0.0982	0.235*
	(0.121)	(0.127)
_cons	-11.02***	-8.115***
	(0.627)	(0.582)
Firm	Yes	Yes
Year	Yes	Yes
N	14488	18649
F	60.741***	44.643***
r2	0.780	0.805

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

As shown in Table 13, the difference-in-differences (DID) coefficient for the impact on patent output in high-tech, heavily polluting firms is 0.365 (statistically significant at the 1% level), while the coefficient for non-high-tech, heavily polluting firms is 0.192 (also significant at the 1% level). A between-group coefficient difference test was similarly conducted, with results summarized in Table 12.

Table 12 Test of differences in coefficients between high-tech heterogeneity groups

Variables	Non-high-tech - high-tech	Freq	p-value
DID	-0.173	100	0.00
Size	-0.137	100	0.00
Lev	-0.154	86	0.14
REC	0.747	0	0.00
INV	-0.414	93	0.07
Cashflow	0.24	13	0.13
Top10	0.203	19	0.19
Balance	0.001	55	0.45
BM	0.209	2	0.02
TMTPay	-0.052	95	0.05
Mshare	0.137	26	0.26
_cons	2.903	0	0.00

Table 12 demonstrates that in all 100 randomized samples, the DID coefficient for patent output in non-high-tech, heavily polluting firms is consistently smaller than that for high-tech counterparts, confirming a statistically significant disparity between the two groups. This implies that the environmental protection tax reform exerted a stronger influence on innovation in high-tech, heavily polluting firms. Two factors likely explain this divergence:

First, innovation incentives differ substantially. High-tech firms prioritize technological innovation as a core competitive strategy. When confronted with environmental tax reforms, these firms are more inclined to increase R&D investments to meet regulatory requirements, thereby driving patent growth. In contrast, non-high-tech firms often rely on conventional production methods with lower dependence on innovation.

Second, innovation capacity varies fundamentally. High-tech firms allocate substantial financial and human resources to R&D, establishing state-of-the-art research centers and attracting top-tier talent. This infrastructure enables them to maintain technological leadership and rapidly adapt existing expertise to environmental challenges—for instance, repurposing core technologies for pollution control or transferring green innovations across business units. Non-high-tech firms, however, lack comparable capabilities in both innovation generation and implementation. Their limited technical expertise and resource constraints result in slower adaptation to regulatory pressures, leading to less efficient improvements in innovation outcomes under the tax reform.

6.Conclusions

As pivotal stakeholders in global environmental governance, emerging economies confront the growth-sustainability paradox: balancing industrial expansion with ecological carrying capacity. This research elucidates the regulatory innovation mechanism by which environmental tax instruments (ETIs) drive technological upgrading in high-pollution industries, demonstrating how Pigouvian taxation transforms the developmental trajectory from reactive remediation to proactive prevention.

Focusing on China's A-share listed companies (2012–2023), we employ a difference-in-differences (DID) methodology to analyze the reform's impact on corporate innovation. This quasi-experimental design compares innovation outcomes between treatment and control groups before and after policy implementation. Results demonstrate that the reform significantly enhanced innovation capabilities in heavily polluting firms, as evidenced by a marked increase in patent applications. These findings remain robust across multiple sensitivity analyses, including parallel trend validation and placebo testing. Mechanism analysis reveals that the policy primarily stimulates innovation by incentivizing increased R&D investments, enabling firms to develop cleaner production technologies. Heterogeneity analysis further identifies stronger innovation-promoting effects for state-owned enterprises, large-scale firms, and high-tech industries, underscoring the role of resource advantages and technological readiness in driving sustainable transitions.

Building on theoretical and empirical findings, this study proposes actionable policy recommendations tailored to the economic realities of China and other developing economies.

First, developing a flexible environmental taxation framework is critical to incentivizing corporate green innovation. Our results indicate that environmental tax reforms effectively stimulate R&D capabilities in polluting industries. To amplify this effect, governments should implement dynamic tax adjustment mechanisms with sector-specific rate differentiation, where tax brackets are calibrated based on industry pollution intensity and technological readiness. For heavily polluting sectors, a graduated progressive tax system could be adopted, imposing higher marginal rates on pollution thresholds. Concurrently, firms exceeding industry averages in clean technology R&D investment should qualify for integrated "R&D tax credit-environmental tax reduction" incentives. This dual mechanism would alleviate transitional costs while strategically channeling R&D resources toward pollution prevention technologies.

Second, establishing a comprehensive green innovation support system is essential to address fragmentation risks in technology commercialization. A three-phase incentive mechanism—combining basic research subsidies, pilot-stage risk compensation, and tax incentives for commercialization—should be implemented. For pollution control technologies developed by heavily polluting firms, government-funded programs could cover up to 40% of R&D costs. Additionally, expedited VAT refunds upon collection should be granted for commercialized green products to enhance market competitiveness. To accelerate technology diffusion, state-owned enterprises (SOEs) could leverage their scale and influence to establish cross-industry green technology platforms, particularly targeting sectors with limited innovation spillovers.

Third, to enhance the coordination of international environmental regulations and design a diversified portfolio of policy instruments, it is imperative to leverage multilateral platforms such as the WTO. In light of the EU Carbon Border Adjustment Mechanism (CBAM) and the UK carbon tax, which have incorporated internationally recognized low-carbon technologies into their tariff reduction frameworks, we propose establishing a comprehensive cross-border green technology certification system. Enterprises that achieve ISO 14034 certification should be eligible for export tariff concessions or rewards in the form of carbon market quotas, thereby promoting the international transfer of low-carbon technologies. Furthermore, the establishment of a global green innovation fund would facilitate access to cutting-edge technologies, addressing the "North-South divide" in low-carbon transition efforts.

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