Journal of Environmental Management 392 (2025) 126682

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Ecological compensation and breakthrough innovation: Evidence from heavily polluting firms

Chao-Fan Chen [a], Zixin Zhou [a], Chuan Li [b], Wei Liu [c,*]

[a] Business School, Beijing Normal University, Beijing, 100875, China
[b] Queen's Business School, Queen's University Belfast, Belfast, BT7 1NN, UK
[c] School of Statistics, Shandong Technology and Business University, Yantai, 264100, China

ARTICLE INFO

Keywords:
Ecological compensation
Breakthrough innovation
Data asset disclosure levels
Innovation risk
Environmental governance

ABSTRACT

The continuous deepening of the concept of green development and the increasing pressure of environmental governance leads great theoretical significance and practical value to explore the impact of the ecological compensation (eco-compensation) policy on the innovation behavior of enterprises. Taking the implementation of China's ecological compensation policy as an exogenous shock, this paper adopts a multi-period difference-in-differences (DID) model to systematically assess the impact of eco-compensation on corporate breakthrough innovation based on the data of A-share listed companies in the heavy pollution industry from 2014 to 2023. The findings indicate that eco-compensation significantly promotes breakthrough innovation activities of heavy polluting firms. Mechanism analysis further reveals that the policy indirectly drives the enhancement of firms' breakthrough innovation capability mainly by improving the level of data asset disclosure, reducing innovation risk and enhancing R&D activity. The heterogeneity analysis reveals that the eco-compensation policy promotes breakthrough innovation more significantly in firms located in regions where big data management institutions remain unreformed, data factor utilization is low, or industry–university–research collaboration is absent. This study theoretically expands the understanding of the impact mechanism of environmental regulation on enterprises' green innovation and enriches the research framework of incentives for breakthrough innovation; in practice, it provides policy references for optimizing the design of eco-compensation policies and guiding heavily polluting enterprises to achieve green transformation and high-quality development.

1. Introduction

Against the backdrop of increasingly severe global climate change and stringent ecological and environmental constraints, promoting the coordination and unity of high-quality economic development and ecological civilization construction has become a core issue of common concern for the academic and policy communities. For heavily polluting industries, long-term reliance on the traditional high-input, high-emission development model has become unsustainable, making the transition to a green and low-carbon development path increasingly urgent. However, the green technology transition is not a simple technology replacement, but involves the disruption and reconstruction of the original technological path, thus requiring enterprises to engage in breakthrough innovation. Unlike incremental innovation, breakthrough innovation implies that firms must go beyond the boundaries of existing knowledge to explore new technologies and reorganize resources (Hu et al., 2024; Byun et al., 2021; Ma et al., 2023; Li et al., 2024; Qamri et al., 2025), and therefore face greater technological uncertainty and investment risks (Sendstad et al., 2021; Wang et al., 2024; Ye et al., 2024). The incentive role of external environmental policies is particularly critical as breakthrough innovations suffer from significant market failures that are difficult to promote by relying solely on firms' spontaneous behavior.

In recent years, much attention has been paid to how environmental policy affects firms' innovative behavior, with Porter hypothesizing that moderately stringent environmental regulations can enhance competitiveness by inducing firms to engage in green innovation through both incentives and compensatory effects (Porter, 1991; Brännlund and Lundgren, 2009). Subsequent empirical studies have further confirmed the role of environmental regulations in promoting green innovation, especially in promoting technological upgrading and increasing R&D investment (Ni et al., 2023; Du et al., 2021; Hsu et al., 2021; Yang et al.,

* Corresponding author. Room 52-201, No.191 Binhai Middle Road, Laishan District, Yantai City, Shandong, China.
E-mail addresses: ccfwyy@163.com (C.-F. Chen), zixinzhou@mail.bnu.edu.cn (Z. Zhou), choices@outlook.com (C. Li), ky2025liu@163.com (W. Liu).

https://doi.org/10.1016/j.jenvman.2025.126682
Received 16 May 2025; Received in revised form 13 July 2025; Accepted 18 July 2025
Available online 28 July 2025
0301-4797/© 2025 Published by Elsevier Ltd.

2024; Li et al., 2025). However, most existing studies focus on incremental innovation, while paying less attention to breakthrough innovation as a distinct mode of innovation. More importantly, the existing literature lacks a systematic and in-depth examination of the internal mechanisms of firms' breakthrough innovation behavior, as well as detailed micro-theoretical and empirical evidence on how firms break through technological path dependence and inertia under the incentives of external policies.

Besides, ecological compensation (eco-compensation), as an emerging market-based environmental governance policy tool in recent years, is gradually playing a broader role in incentives and constraints (Shang et al., 2018; Hunjra et al., 2024; Zhou et al., 2023). Based on the principle of "the beneficiary pays, the destroyer compensates", the eco-compensation system guides local governments and enterprises to improve their environmental governance performance through financial incentives and penalties (Shen et al., 2021; Qamri et al., 2022; Xue et al., 2023; Guan et al., 2024; Yang et al., 2024). The Chinese government has successively issued policy documents related to ecological protection compensation, such as the *Opinions on the Establishment and Improvement of Ecological Protection Compensation Mechanisms* issued by the General Office of the State Council and the *Guiding Opinions on Accelerating the Establishment of Horizontal Ecological Protection Compensation Mechanisms Upstream and Downstream of Watersheds* jointly issued by the Ministry of Finance and the Ministry of Ecology and Environment, thereby laying the institutional foundation for a more comprehensive and standardized eco-compensation framework. However, existing studies have mainly focused on the macro-level effects of eco-compensation policies on environmental quality improvement and regional development coordination (Cao et al., 2021, 2022; Hu et al., 2023; Li et al., 2024), and have not explored in depth how eco-compensation policies act on breakthrough innovation behaviors at the enterprise level, nor have they systematically revealed their internal transmission mechanisms and boundary conditions. This lack of micro-level mechanisms and heterogeneity considerations constrains academic understanding of the economic effects of eco-compensation policies and hampers policymakers' ability to design targeted and effective policy instruments. Fig. 1 provides visual corroboration of the research motivation of this study. The yellow area in the figure indicates the number of breakthrough innovations per year for the logarithmic treatment, the green area indicates the number of breakthrough technology types across IPC level 2 categories, and the broken line gives the year-on-year growth rate of the number of breakthrough innovations. It can be seen that from 2014 to 2018, the number of breakthrough innovations and cross-border technology types both showed a steady increase, although the growth rate fluctuated. In 2019, driven by a wave of external green investment and the fulfillment of the first-round assessment of *China's National Campaign for Pollution Prevention and Control*, breakthrough innovations experienced a brief peak before falling back quickly. Since 2020, the growth rate has been mostly negative. The "rise-then-fall" pattern in structural changes indicates that without continuous incentives, enterprises' enthusiasm for high-risk breakthrough exploration is vulnerable to macroeconomic fluctuations and cost pressures, making it challenging to sustain innovation momentum through market forces alone. Therefore, it is urgent to examine whether policy tools such as eco-compensation characterised by financial incentives and penalties can effectively cushion the decline in innovation and reactivate firms' breakthrough innovation. This question not only has significant practical relevance but also provides a clear empirical foundation for the causality test conducted in this paper.

In view of the above practical issues and gaps in the literature, this paper takes the implementation of China's eco-compensation policy as a quasi-natural experiment. Using data on A-share listed companies in heavily polluting industries from 2014 to 2023, it employs a multi-period difference-in-differences (DID) approach to systematically examine the causal impact of the policy on firms' breakthrough innovation. More importantly, this paper develops the analysis in depth from two dimensions: micro-mechanism and heterogeneity. At the mechanism level, this paper explores how eco-compensation policy indirectly promotes breakthrough innovation behavior of enterprises by enhancing their data asset disclosure level, reducing innovation risk and increasing R&D activity. At the heterogeneity level, it further explores how differences in the institutional environment, firms' resource utilization, and the level of industry-academia-research collaboration modulate the policy's effects. Through the above analysis, this paper tries to answer the following core questions: can the eco-compensation policy significantly promote the breakthrough innovation of heavily polluted enterprises? What are the characteristics of its mechanism and condition boundaries?

The contribution of this paper is reflected in the following aspects: firstly, this paper starts from the micro perspective of breakthrough innovation, systematically evaluates the innovation incentive effect of the eco-compensation policy, expands the existing research boundaries

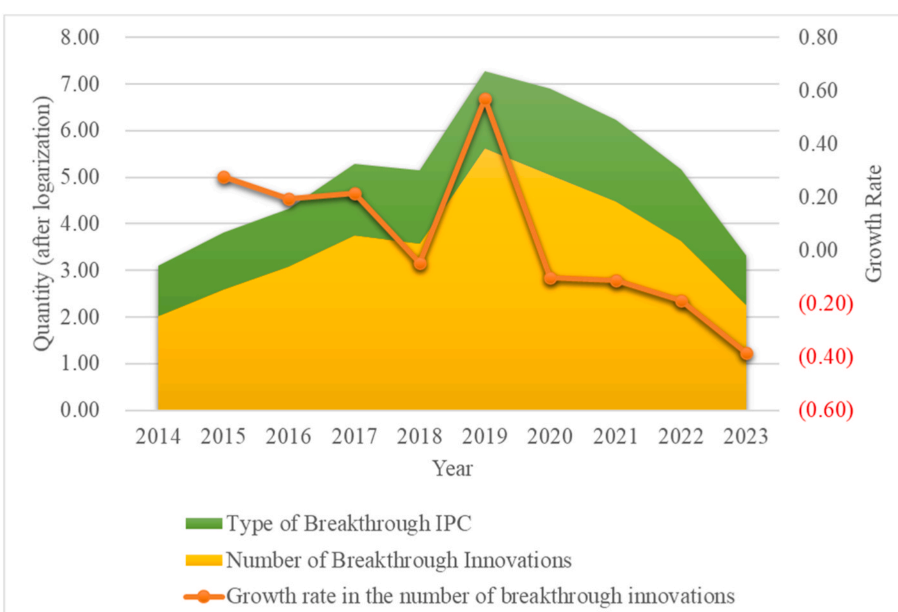

Fig. 1. Breakthrough innovations in China's heavily polluting firms, 2014–2023.

of the impact of environmental regulation on corporate innovation, makes up for the limitations of the existing literature that focuses on incremental innovation, and deepens the theoretical explanatory framework of green innovation policy. Secondly, by analyzing three micro-level mechanisms—data asset disclosure, innovation risk control, and R&D activity—this paper reveals the internal logical chain through which eco-compensation policies drive breakthrough innovation, thereby refining the academic understanding of the micro-level transmission paths of environmental policy. Finally, this paper further identifies the heterogeneity of policy effects across different institutional environments, resource utilization, and levels of collaboration, and proposes a context-specific and targeted design of policy incentives, providing both an empirical basis and practical guidance for the differentiated implementation of eco-compensation policies.

The rest of the paper is organized as follows: Part II is the theoretical analysis and research hypotheses. Part III is the research design, detailing the data sources, variable definitions and modeling methods; Part IV reports the baseline regression results and conducts a series of robustness tests; Part V conducts an in-depth analysis of the mechanism effects; Part VI explores the heterogeneity of the policy effects; and Part VII summarizes the findings of the full paper and puts forward targeted policy recommendations and future research directions.

2. Theoretical analysis and research hypotheses

2.1. Eco-compensation and breakthrough innovations for heavily polluting enterprises

The Porter hypothesis provides an important theoretical framework in understanding the mechanism by which environmental policies affect firms' innovative behavior. Porter (1991) pointed out that rationally designed environmental regulations can induce firms to improve their processes and products through incentive effects and innovation compensation effects, thus creating a positive relationship between environmental improvements and economic efficiency gains. Subsequent studies have further emphasized that environmental policies not only raise the cost of emissions, but also affect firms' willingness to invest in innovation by adjusting their expected returns and investment decision boundaries (Kyaw, 2022). In particular, policy incentives are especially important for high-risk innovations in contexts where externalities are significant and market failures are prominent. Breakthrough innovation involves the disruptive reconfiguration of established technology paths, which is highly uncertain and exploratory compared to incremental innovation (Verhoeven et al., 2025; Wu et al., 2020). Firms, when faced with high environmental uncertainty and technological risk, tend to maintain path dependence and avoid allocating resources to exploratory projects with high probability of failure. Therefore, how to reduce the opportunity cost for firms to engage in breakthrough innovations through external incentives has become an important objective of policy design. Eco-compensation policy, characterized by fiscal incentives and penalties, essentially aims to internalize the environmental externalities of local governments and enterprises by linking environmental quality assessment outcomes to fiscal allocations, thereby adjusting the structure of returns on green investment.

Theoretically derived, eco-compensation policy may act on the breakthrough innovation decisions of heavily polluting firms through the following three interrelated channels: first, according to the theory of the innovation compensation effect, financial compensation raises the expected return on green technology investments. Under such a compensation mechanism, firms that reduce pollution emissions through innovation can receive additional fiscal rewards or avoid fiscal penalties, thereby significantly enhancing the net present value of their innovative activities. For breakthrough innovation projects that were previously hindered by high uncertainty, this enhancement of expected returns serves as an important incentive for firms to increase their exploratory investments. Second, from the perspective of risk mitigation, the financial reward-and-penalty mechanism helps hedge, to some extent, the upfront investment risks associated with breakthrough innovation. Breakthrough innovation is characterized by high capital demand, long payback period, and high probability of failure (Datta and Srivastava, 2023; Gao et al., 2025). The continuity and stability of the eco-compensation policy provides firms with strong policy expectations and partial revenue guarantees, which reduces the financial shock caused by the failure of the innovation project, thus increasing the tolerance of firms to undertake high-risk projects. Third, according to the path dependence theory, enterprises tend to continue to invest along the established path of success, resulting in technological evolution limited to the local optimum. Eco-compensation, by directing firms' attention to new performance indicators, compels them to re-evaluate their technological choices, overcome the inertia of prior investments, and explore cross-boundary or entirely new technological directions. As a result, the likelihood of breakthrough innovation is significantly increased by policy intervention.

Based on the above theoretical logic, this paper puts forward the following research hypothesis: the eco-compensation policy has the potential to significantly promote the breakthrough innovation behavior of heavily polluting enterprises.

2.2. The level of data asset disclosure

In the modern enterprise innovation system, data has become a core production factor and a key innovation resource (Gao et al., 2023; Xu, 2021). Especially in the exploratory activities for breakthrough innovation, high-quality data asset management and adequate information disclosure can help enterprises identify potential technological opportunities, optimize resource allocation, and enhance the efficiency of knowledge reorganization. However, due to traditional management concepts and cost considerations, enterprises are often reluctant to systematically manage and disclose their data resources. In this context, the external environmental policy through mandatory disclosure of information and incentives and constraints, may inadvertently promote enterprises to strengthen the construction and management of data assets, thus creating favorable conditions for breakthrough innovation.

The implementation of eco-compensation policy requires local governments and relevant enterprises to continuously monitor and disclose the level of pollutant emissions, governance measures and effectiveness, which essentially raises the information transparency requirements of enterprises in the field of environmental data. According to the theory of institutional response, enterprises facing mandatory external institutional pressure tend to enhance compliance and external evaluation by strengthening internal resource integration and organizational capacity building. Therefore, under the pressure of eco-compensation assessment, heavily polluting enterprises have the incentive to improve their internal data collection, processing and disclosure system, not only at the level of emission data, but also in the systematic management and presentation of green assets, technological innovations, and other information in the overall operation process.

This process may indirectly improve the level of data asset disclosure of enterprises, thus bringing three aspects of breakthrough innovation promotion effects: first, the improvement of data asset management system improves the ability of enterprises to identify cross-border technological opportunities, providing a rich and systematic knowledge base for technological restructuring (Yu et al., 2022; Lyu et al., 2024; Liu et al., 2024); second, transparent data disclosure strengthens the image of the enterprise in the capital market and policy evaluation, reduces external financing barriers, and helps alleviate the common financial constraints in the process of breakthrough innovation; third, the data-driven management model facilitates exploratory learning and rapid trial-and-error within enterprises, enhancing their adaptability and flexibility in the field of emerging technologies.

However, whether the improved level of data asset disclosure can truly translate into enhanced breakthrough innovation capability depends on firms' ability to effectively utilize the newly established information resource systems and make leapfrogging technological decisions in a highly competitive and risky environment. Based on the above theoretical analysis, this paper puts forward the following research hypothesis: eco-compensation policy indirectly promotes the breakthrough innovation behavior of enterprises by enhancing their data asset information disclosure level.

2.3. Innovation risk

Breakthrough innovation, as a highly exploratory and disruptive innovation activity, is essentially characterized by highly uncertain outcomes, long lead times, and high probability of failure (Kraus et al., 2023; Rafik, 2022; Wu et al., 2024). Firms are particularly sensitive to changes in the external environment as they usually need to weigh high potential returns against high real risks when deciding whether to engage in breakthrough innovation. In the absence of clear incentives or safeguards, firms often tend to choose incremental innovations and maintain established paths for risk-averse motives, rather than investing resources in high-risk exploration.

Eco-compensation schemes may serve a risk-mitigating function in firms' breakthrough innovation decisions by establishing financial incentives and penalties. On the one hand, the implementation of the eco-compensation policy implies that if enterprises achieve pollution reduction through technological upgrading, they can not only avoid financial deductions but also become eligible for fiscal rewards. On the other hand, failure to meet the required standards will directly result in financial losses and reputational pressure. According to expected utility theory, when the policy incentives are strong enough, the utility function of enterprises may be shifted in the face of innovation risk, i.e., risk avoidance tendency is weakened, and risk-taking ability is enhanced (Zhong et al., 2025; Shao and Xu, 2024). Specifically, eco-compensation policies may reduce the perceived innovation risk faced by firms through two logical paths: first, the revenue security path. Fiscal incentives enhance the marginal returns to successful green technology investments, lowering net loss expectations in the event of innovation failure and increasing the expected utility of breakthrough innovations; and the second is the path of internalization of the cost of failure. Environmental inspections and assessments increase the economic costs of pollution control failures, making the maintenance of the old technology path itself more risky. Under this dual effect, the risk disadvantage of breakthrough versus incremental innovation is partially offset, and firms are more motivated to engage in high-uncertainty exploration. Based on the above analysis, this paper proposes the following research hypothesis: the eco-compensation policy indirectly promotes breakthrough innovation behavior by reducing the perceived innovation risk of firms.

2.4. R&D activity

The degree of activity of an enterprise's internal R&D system is one of the key organizational conditions for breakthrough innovation to be successfully nurtured and promoted (Ferreira et al., 2023; Zhu et al., 2025). Unlike incremental innovation, which relies on the optimization of existing processes, breakthrough innovation requires companies to have stronger exploratory learning capabilities, cross-boundary knowledge integration capabilities, and a highly fault-tolerant R&D organizational culture. Only when the internal R&D activity is strong and the knowledge production and resource flow mechanism is sufficient can breakthrough innovation exploration with high uncertainty and high failure rate be supported. Therefore, external environmental policies that can promote internal R&D activity through incentive effects may indirectly drive breakthrough innovation behavior.

Eco-compensation policy directly links the effectiveness of pollution control with economic benefits through the financial reward and punishment mechanism, which generates continuous and specific performance pressure on enterprises. According to Organizational Response Theory (ORT), firms will usually strengthen internal capacity building to enhance adaptability and legitimacy in the face of external coercive institutional pressures. Specifically at the R&D level, in response to environmental assessment requirements and compensation incentives, firms are motivated to increase R&D investment in green technologies, expand their R&D teams, and enhance the exploratory nature of projects—fostering a more dynamic R&D culture at the organizational level.

In addition, the knowledge base of breakthrough innovation often requires cross-sectoral collaboration and cross-disciplinary combinations (Pedersen et al., 2021; González-Piñero et al., 2021). The eco-compensation policy promotes enterprises to pay attention to green transformation, which prompts them to introduce more talents and knowledge elements from diversified backgrounds into their R&D organizations, increasing the knowledge heterogeneity and restructuring activity in the R&D process, and providing soil for technological leapfrogging. Based on the above analysis, this paper puts forward the following research hypothesis: the eco-compensation policy indirectly promotes the breakthrough innovation behavior of enterprises by enhancing their internal R&D activity.

3. Research design

3.1. Data sources and processing

In order to test the impact of eco-compensation policy on breakthrough innovation of enterprises, this paper takes A-share listed companies in heavy pollution industry as the research sample from 2014 to 2023. The industry division criteria refer to the Ministry of Ecology and Environment's "Listed Company Environmental Verification Industry Classification and Management Directory" and the classification method proposed by Hu et al. (2021), which covers the industry codes of B06-B12, C13, C15, C17, C19, C22, C25-C32, D44 and D45.[1] Based on considerations of data reliability and sample validity, we first exclude companies with abnormal operations or delisting risks, such as ST and PT firms, as well as financial enterprises. Second, observations with missing key variables that prevent inclusion in the empirical analysis are removed. In order to reduce the interference of extreme values on statistical inference, continuous type variables are reduced-tailed at 1% and 99% quartiles. The final screening yielded 9780 firm-year observations, and the related financial and governance data were obtained from the Wind database.

3.2. Selection of variables

1. Breakthrough innovation (*BrthInno*). Breakthrough innovation refers to the enterprise's subversion and reconstruction of the existing technology path, with a high degree of uncertainty and exploration, the core of which is to break the boundaries of the existing knowledge, and realize the transformation from "path dependence" to "path jumping". Referring to the research ideas of Ahuja and Lampert (2001) and Bi et al. (2022), this paper constructs a patent originality index based on patent classification information to measure the breakthrough innovation capability of enterprises. Patent applications, as the most accessible and actionable source of data on firms' innovation activities, together with their citation patterns, can reveal the sources of technological knowledge and the degree of novelty to a certain extent. When an enterprise cites a patent classification in a patent application that has not previously appeared in its existing application records, and the classification crosses the second level of the International Patent Classification System (IPC),

[1] Data source: https://www.mca.gov.cn/images3/www/file/201711/1509495881341.pdf.

it indicates that it has conducted new exploration outside the original technological boundaries, and embodies significant technological jump characteristics and strong original innovation capability. At the operational level, the process is as follows: first, identify all patents cited in each enterprise's patent application and determine whether any citations cross the second level of IPC classification. Second, classify those meeting this criterion as breakthrough innovation patents. Third, calculate the proportion of breakthrough patents to the total number of patent applications filed by the enterprise in the same year, which serves as a measure of annual breakthrough innovation intensity. The higher the value of this indicator, the greater the degree of technological cross-border exploration carried out by the enterprise in the relevant year, and the stronger the breakthrough innovation capability.

2. Ecological compensation (*EC*). Eco-compensation is an important institutional arrangement in China, aimed at incentivizing local governments to improve ecological and environmental quality through a system of financial rewards and penalties, and at promoting coordinated regional ecological protection and sustainable development. This policy reflects the Chinese government's innovative approach to promoting green production and green lifestyles through market-based and rule-of-law approaches under the strategic framework of building an ecological civilization. In 2016, the *Opinions on the Establishment and Improvement of Ecological Protection Compensation Mechanisms*, and the *Guiding Opinions on Accelerating the Establishment of Horizontal Ecological Protection Compensation Mechanisms Upstream and Downstream of Watersheds*, which provide an institutional basis and practical guidelines for the piloting and popularization of eco-compensation policies. In this study, based on the above policy documents, the eco-compensation policy is regarded as a quasi-natural experiment, and the eco-compensation variables are constructed to identify its impact on corporate breakthrough innovation. It is defined as follows: for each listed company *i*, the variable takes a value of 1 starting from year *t* if the city where it is located formally implements the policy in year *t*; otherwise, if the policy is not implemented in that city during the study period, the variable remains 0 throughout.
3. Control variables: *Size* is expressed as the natural logarithm of the firm's total assets, reflecting the firm's resource base and risk tolerance. *Lev* is measured by gearing ratio to capture the possible impact of the level of financial leverage on the innovation decision. *ListAge* refers to the survival time of the firm since its IPO and is measured in terms of years to control for differences in the life cycle stages of the firm. *Dual* is a dummy variable that takes the value of 1 if the chairman of the board and the general manager are the same person, and 0 otherwise, reflecting the degree of centralization of the corporate governance structure. *TobinQ* is calculated as the ratio of the firm's market capitalization to the book value of its assets, reflecting the firm's market expectations and investment opportunities. The financing constraint indicator is the *SA index* (Hadlock and Pierce, 2010), which measures the degree of external financing obstacles faced by the firm. *ROA* is expressed as the ratio of net profit to average total assets, which is used to control the business performance of the firm.

3.3. Model construction

In order to systematically assess the impact of eco-compensation policy on the breakthrough innovation capability of enterprises, this paper constructs a multi-period DID for empirical testing:

$$BrthInno_{it} = \alpha + \beta_1 EC_{it} + \gamma X_{it} + \mu_i + \lambda_t + \epsilon_{it} \quad (1)$$

Where $BrthInno_{it}$ denotes the breakthrough innovation intensity of firm *i* in year *t*, as the dependent variable; EC_{it} is the core explanatory variable, which denotes the implementation of the eco-compensation policy, and takes the value of 1 when the city where the firm is located has already implemented the policy in year *t*, and 0 otherwise; X_{it} is the set of control variables. μ_i and λ_t denote firm fixed effects and year fixed effects, respectively, to control for unobservable time-invariant characteristics of firms and systematic effects of macroeconomic fluctuations; ϵ_{it} is the random error term. Among them, the estimated value of the core parameter β_1 reflects the direction and magnitude of the impact of the eco-compensation policy on the breakthrough innovation ability of enterprises. If $\beta_1 > 0$ is significant, it indicates that eco-compensation effectively promotes the breakthrough innovation activities of heavily polluting enterprises.

4. Empirical results and analysis

4.1. Descriptive statistics

Table 1 reports the descriptive statistics of the main variables of this paper. Given the relatively small magnitude of breakthrough innovation intensity, we scale the variable by multiplying it by 100. Specifically, the sample mean of breakthrough innovation intensity (*BrthInno*) is 2.734. Meanwhile, the standard deviation is 4.590, indicating a considerable degree of heterogeneity in breakthrough innovation activities among firms. The core explanatory variable, *EC*, has a mean value of 0.137, indicating that approximately 13.7% of the firm-year observations in the sample were subject to policy intervention during the study period.

4.2. Benchmark regression

Table 2 presents the results of the benchmark regressions on the impact of eco-compensation policies on firms' breakthrough innovations. Columns (1) to (3) present regressions with varying fixed effect specifications to progressively test the robustness of the policy effect estimates. First, the core explanatory variable *EC* presents a significant positive effect in all models and is significant at the 1% level, verifying that the policy of eco-compensation can effectively promote breakthrough innovation of enterprises. In column (1), without controlling for fixed effects, the coefficient of *EC* is 1.1580. After introducing year fixed effects in column (2), the coefficient slightly decreases to 1.0177 but remains highly significant. When both firm and year fixed effects are controlled for in column (3), the coefficient increases to 1.2813 and remains significant, suggesting that the results are robust across different model specifications.

4.3. Robustness tests

1. Parallel trend test

In order to verify the validity of the multi-period DID modeling setup, this paper adopts the event study method to plot the trend of the dynamic effects of the treatment and control groups before and after the implementation of the policy, and the results are shown in Fig. 2. From Fig. 2, it can be observed that before the policy implementation, i.e., during the period from −5 to −1 relative to the policy time point, the

Table 1
Descriptive statistics.

Variable	N	Mean	SD	Min	p50	Max
BrthInno	9780	2.734	4.590	0	1	30
EC	9780	0.137	0.344	0	0	1
Size	9780	22.35	1.296	19.78	22.15	26.16
Lev	9780	0.393	0.198	0.0505	0.380	0.873
ListAge	9780	2.183	0.917	0	2.398	3.332
Dual	9780	0.284	0.451	0	0	1
TobinQ	9780	2.023	1.284	0.847	1.593	7.654
SA	9780	−3.885	0.245	−4.405	−3.890	−3.047
ROA	9780	0.0442	0.0669	−0.182	0.0408	0.242

Table 2
Benchmark regression.

Variable	(1)	(2)	(3)
	BrthInno	BrthInno	BrthInno
EC	1.1580***	1.0177***	1.2813***
	(0.1469)	(0.1467)	(0.2155)
Size	1.1739***	1.1505***	1.1557***
	(0.0556)	(0.0558)	(0.1487)
Lev	0.3997	0.4659*	−0.4764
	(0.2637)	(0.2652)	(0.4546)
ListAge	−2.0438***	−1.9863***	−4.1151***
	(0.0945)	(0.0942)	(0.2539)
Dual	−0.1806*	−0.2047**	0.0830
	(0.1038)	(0.1030)	(0.1507)
TobinQ	0.0742**	0.0834**	0.0954*
	(0.0343)	(0.0354)	(0.0568)
SA	0.0301	0.2907	1.5137
	(0.2042)	(0.2321)	(1.2363)
ROA	−1.1285	−1.7808**	−2.5490***
	(0.8286)	(0.8357)	(0.8690)
Constant	−19.2927***	−17.8722***	−8.3232
	(1.4254)	(1.5321)	(5.6651)
Firm FE	N	N	Y
Year FE	N	Y	Y
Observations	9780	9780	9731
Adj.R2	0.158	0.172	0.334

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

estimated value of the treatment effect is close to 0 as a whole, and the confidence intervals all contain zero, and there is no significant trend difference, which indicates that the development trend of the breakthrough innovation of the treatment group and the control group before the implementation of the policy is basically the same, and it is in line with the basic requirements of the parallel trend assumption. After the policy implementation, the treatment effect increases rapidly and remains significantly positive for several years, indicating that the eco-compensation policy significantly promotes firms' breakthrough innovation in the post-implementation period.

2. Placebo test

In order to further verify the robustness of the regression results and exclude chance estimation problems due to sample selection, model setting or other unobserved factors, this paper adopts the replacement test method to conduct the placebo test. This is done by randomly disrupting the eco-compensation policy variable on the basis of keeping the sample structure unchanged and regressing it again after each replacement, recording the estimated coefficients of *EC* and their standard errors in each dummy regression, and repeating it for 500 times to form the distribution of the pseudo-policy effect. The findings are tested for statistical robustness by comparing the true estimated coefficients to this random distribution. Fig. 3 illustrates the results of the permutation test. It can be observed that most of the estimated values of the pseudo-policy effects are densely distributed around zero and feature an approximately symmetric bell-shaped distribution; while the real estimated *EC* coefficients are far away from this central distribution region and are clearly located in the remote right-hand side and correspond to very small pseudo-p-values. This suggests that if the policy variables are randomly assigned, they are unlikely to produce positive breakthrough innovation effects similar to the actual results.

3. Robustness test

First, considering that different cities may have systematic differences in their level of economic development, industrial structure, and policy implementation efforts, which, if not controlled for, may lead to omitted variable bias. Therefore, Column (1) in Table 3 introduces city fixed effects based on the baseline model to eliminate the interference of city-level unobservable heterogeneity on the regression results. The regression results show that the estimated coefficient of *EC* is 1.2879 and significant at the 1 % level, indicating that the positive facilitation of breakthrough innovations by the eco-compensation policy still exists robustly when city heterogeneity is adequately controlled.

Second, in order to further enhance the comparability of the distribution of covariates between the treatment group and the control group, and to reduce the estimation bias that may be caused by the differences in the initial characteristics of the samples, this paper adopts the entropy balancing method to weight the samples for adjustment. By optimizing the assignment, the entropy balance method makes the treatment group and the control group strictly balanced in mean, variance and higher-order moments at the same time, which has higher matching accuracy compared with the traditional propensity score method. The results in Column (2) show that the estimated coefficient of *EC* is 1.3815 after entropy balancing treatment and is significant at 1 % level, which further verifies that the conclusion that policy promotes breakthrough

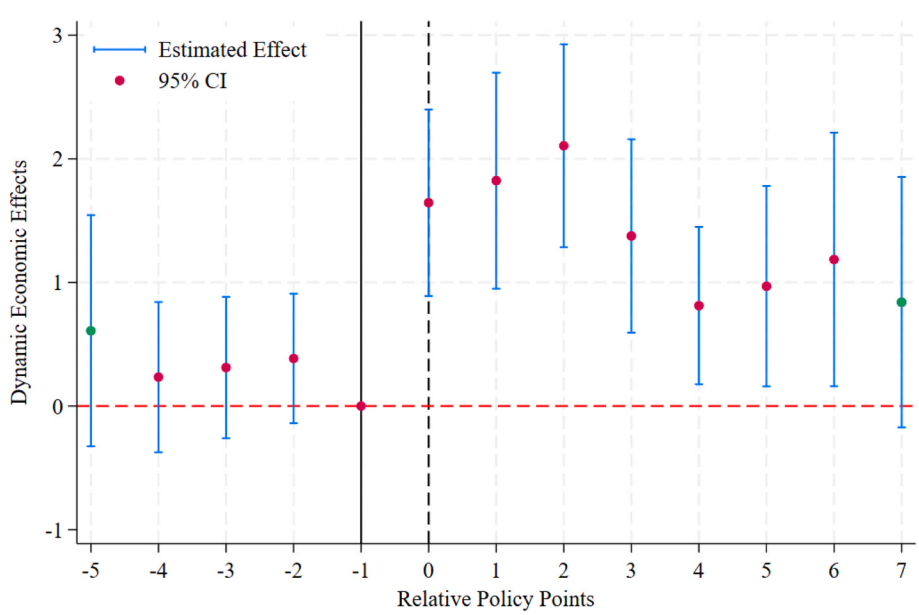

Fig. 2. Parallel trend test.

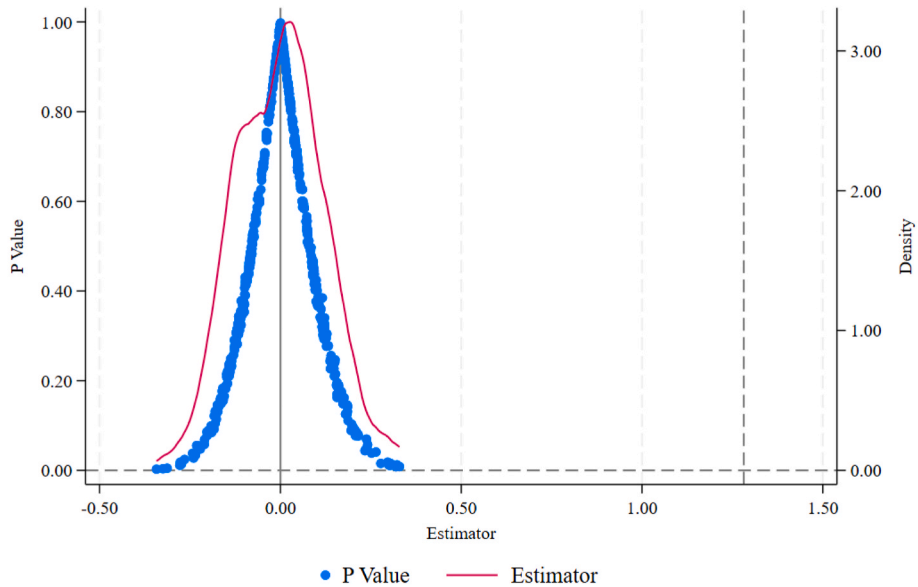

Fig. 3. Placebo test.

Table 3
Robustness test.

Variable	(1)	(2)	(3)
	City Fixed Effects	Entropy Balance Method	PSM 1:1
	BrthInno	BrthInno	BrthInno
EC	1.2879***	1.3815***	1.7294***
	(0.2159)	(0.2186)	(0.3051)
Control	Y	Y	Y
N	9727	9731	2901
Adj.R2	0.334	0.341	0.318
Firm FE	Y	Y	Y
Year FE	Y	Y	Y
City FE	Y	N	N

innovations of firms is not affected by the initial difference of samples.

Finally, to address potential self-selection bias where firm characteristics may influence both the timing of policy implementation in their cities and their own innovation activity. This paper employs a 1:1 propensity score matching method to reconstruct the treatment and control groups. By estimating policy effects on comparable samples, the endogeneity problem caused by sample selectivity can be effectively alleviated. The regression results in Table 3 of Column (3) show that the *EC* coefficient is 1.7294 and significant at the 1 % level, which further consolidates the robustness of the policy's effect on breakthrough innovation promotion.

5. Mechanism testing

In order to further reveal the intrinsic role path of eco-compensation policy on the breakthrough innovation of enterprises, this paper sets the following mechanism effect regression model based on the idea of mediation effect analysis:

$$M_{it} = \alpha + \beta EC_{it} + \gamma X_{it} + \mu_i + \lambda_t + \epsilon_{it} \tag{2}$$

Where M_{it} denotes the mechanism variables, specifically including the level of data asset disclosure (*DisDaAs*), innovation risk (*InnoRisk*) and R&D activity (*RD_Act*); EC_{it} is a dummy variable for eco-compensation policy; X_{it} is the set of control variables; μ_i and λ_t are the firm fixed effects and year fixed effects, respectively; ϵ_{it} is the random error term. In this setting, the focus is on whether policies indirectly drive firms' breakthrough innovation capabilities by improving the level of data asset management, reducing the risk of innovation failure, and increasing the activity of R&D organizations.

The definition of the mechanism variables is as follows: Data Asset Information Disclosure Level (*DisDaAs*) reflects a company's ability to identify, manage, and communicate its core data resources externally. Referring to the method proposed by Niu et al. (2024), this paper constructs a dictionary system based on the core terms of "data assets" and "data resources" defined in the "Data Asset Management Practice White Paper (Version 4.0)" published by the China Academy of Information and Communications Technology (CAICT). The system uses "seed words + Word2Vec extended words" and employs a deep learning model to select high-frequency words most closely related to the seed words, while excluding ambiguous terms (e.g., "basic information"). Finally, the data asset disclosure index is calculated using the following formula: $DisDaAs_{it} = \frac{\sum_{n=1}^{N} DictionaryWords_{itn}}{TotalWords_{it}} \times 100$. The numerator is the total frequency of dictionary terms appearing in the annual report of the *i*-th company in the year, and the denominator is the total number of words in the annual report (excluding English and numerical parts). The higher the indicator, the stronger the company's ability to define, organize, and disseminate data assets. Innovation Risk (*InnoRisk*) is used to measure the potential probability of failure in converting innovation investment into commercial value. Referring to Wang et al. (2019), if a company's R&D expenditure growth rate in the current year is higher than the net profit growth rate in the following year, the innovation activities are deemed to have failed to achieve commercial returns, and a value of 1 is assigned; otherwise, a value of 0 is assigned. This indicator can identify the risk of disruption in the conversion path of a company's innovation output. R&D activity (*RD_Act*) measures the level of activity of a company's internal knowledge production system. Referring to Xiang et al. (2024), the indicator is calculated as the proportion of R&D personnel to the total number of employees. A higher proportion indicates stronger internal organizational support for innovation activities, as well as higher sustained innovation capabilities and exploratory intentions.

Table 4 reports the regression results of the eco-compensation policy on various mechanism variables. In terms of data asset information disclosure level (*DisDaAs*), the *EC* coefficient is 0.0048, which is significantly positive at the 1% level. This indicates that the policy has promoted enterprises' awareness of the importance of data assets and their management practices, prompting enterprises to increase the sorting, definition, and external disclosure of internal data resources, thereby providing a more solid data foundation and knowledge spillover

Table 4
Mechanism effect tests.

Variable	(1)	(2)	(3)
	DisDaAs	InnoRisk	RD_Act
EC	0.0048***	−0.0786***	0.6402**
	(0.0014)	(0.0297)	(0.2543)
Control	Y	Y	Y
N	9731	9731	9731
Adj.R2	0.339	0.149	0.780
Firm FE	Y	Y	Y
Year FE	Y	Y	Y

conditions for breakthrough innovation. From an innovation theory perspective, the deepening utilization of data assets helps expand the knowledge boundaries of enterprises, increase the possibility of cross-domain combination innovation, and thereby gain a first-mover advantage in technological path leaps. In terms of innovation risk (*InnoRisk*), the *EC* coefficient is −0.0786, which is significantly negative at the 1% level, indicating that the implementation of the policy has effectively reduced the probability of failure in the innovation process of enterprises. This result indicates that environmental regulation policies can enhance enterprises' awareness of the necessity of green transformation and their willingness to invest, guiding enterprises to focus more on the feasibility and commercial conversion potential of innovation projects, reduce high-investment, low-output projects, optimize the allocation of innovation resources, and improve innovation output efficiency. In terms of R&D activity (*RD_Act*), the *EC* coefficient is 0.6402, which is significantly positive at the 5 % level, indicating that the policy implementation has prompted enterprises to increase R&D personnel investment and strengthen internal knowledge production systems. This suggests that eco-compensation policies not only influence corporate decision-making through financial incentives but also exert profound impacts on internal organizational resource allocation, promoting the activation and sustainability of R&D systems, thereby providing the necessary human capital and organizational support to facilitate breakthrough innovations.

6. Further analysis

6.1. Reform of big data management organization

Based on the "National Big Data Comprehensive Pilot Zone Construction Plan", this paper constructs a dummy variable equal to 1 if the city where a firm is located has been designated as a national big data comprehensive pilot zone or has established a big data management agency, and 0 otherwise. Based on this criterion, the sample is divided into two groups. Regression results show that, from the perspective of big data management agency reform, the promotional effect of eco-compensation policies is more significant in regions that have not undergone management agency reform. With an *EC* coefficient of 1.2710 and significant at the 1 % level (Table 5). In reform regions, although the policy effect is positive, it does not reach the significant level. This indicates that in regions where the big data governance system is not yet fully developed, enterprises are more sensitive to policy incentives, and the marginal promotional effect of policies on breakthrough innovation is more pronounced, highlighting the important influence of the completeness of the institutional environment on the policy transmission mechanism.

6.2. Level of utilization of data elements

Following the method of Shi et al. (2023), this study constructs an annual index of data element utilization at the enterprise level by counting the frequency with which five key terms related to artificial intelligence, blockchain, cloud computing, big data technologies, and application levels appear in firms' annual reports. After standardization, the index is used to divide the sample into high and low data element utilization groups based on the annual median. Empirical results indicate that in the low data element utilization group, the eco-compensation policies have a more significant promotional effect on breakthrough innovation in enterprises; whereas in the high data element utilization group, although the policy effect is positive, it does not reach statistical significance. This finding indicates that firms with weaker data infrastructures exhibit greater innovation potential when subjected to external policy incentives. Moreover, policy incentives play a more pronounced marginal role in bolstering the innovative vitality of groups with inadequate resource endowments. This may be because, for companies with weak data infrastructure, external policy incentives can serve as a form of compensation. Due to resource constraints, these companies may be unable to independently invest substantial funds in research and development and innovation. When the government provides policy incentives, such as financial subsidies, tax breaks, or technical support, these companies can leverage these additional resources to overcome their inherent resource deficiencies, thereby unlocking greater innovation potential.

6.3. Industry-university-research cooperation

This paper categorizes enterprises based on whether they jointly apply for cooperative innovation patents with universities, research institutes, or other enterprises. Enterprises with cooperative innovation patents are assigned a value of 1, while those without are assigned a value of 0. The regression results show that in enterprises without industry-academia-research cooperation, the eco-compensation policy has a significant promotional effect on breakthrough innovation. However, in the group of enterprises with industry-academia-research cooperation, although the policy coefficient is positive, it does not reach a significant level. This may suggest that companies lacking the ability to integrate external innovation resources are more inclined to actively explore new paths under policy incentives, thereby demonstrating stronger breakthrough innovation responses.

Fig. 4 further illustrates the results of the heterogeneity test. As can

Table 5
Heterogeneity test.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	Reform of big data management organization		Level of utilization of data elements		Industry-university-research cooperation	
	No	Yes	Low	High	No	Yes
	BrthInno	BrthInno	BrthInno	BrthInno	BrthInno	BrthInno
EC	1.2710***	1.1723	1.2586***	1.0650	1.1792***	2.6385
	(0.3646)	(0.8036)	(0.2546)	(0.6732)	(0.2197)	(1.7555)
Control	Y	Y	Y	Y	Y	Y
N	4512	5016	6295	3055	9250	416
Adj.R2	0.351	0.348	0.350	0.336	0.333	0.383
Firm FE	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y

be observed from the figure, in regions where big data management institutions have not been reformed, enterprises with low data element utilization levels, and enterprises lacking industry-academia-research collaboration, the point estimates of *EC* are generally higher than those of other groups, and the confidence intervals are relatively concentrated, indicating that the policy promotion effect is both significant and robust. In contrast, in regions with reformed big data management institutions, enterprises with high data element utilization levels, and those with industry-academia-research collaboration, while the point estimates remain positive, the confidence intervals have significantly expanded, and estimation precision has decreased, indicating that the policy effects have weakened to some extent and uncertainty has increased.

7. Conclusion and policy implications

7.1. Conclusion

This study takes the implementation of China's eco-compensation policy as a quasi-natural experiment and, based on data from A-share listed companies in heavily polluting industries from 2014 to 2023, systematically assesses the policy's role in promoting breakthrough innovation among enterprises, while also conducting an in-depth analysis of its underlying mechanisms and heterogeneous effects. The study finds that eco-compensation policies significantly promote breakthrough innovation activities in heavily polluting enterprises. This positive effect remains robust across a variety of robustness checks, confirming that green regulatory policies, as external sources of pressure, can effectively incentivize firms to break away from existing technological path dependencies and pursue cross-boundary technological exploration and innovation. Further mechanism analysis indicates that eco-compensation policies mainly drive breakthrough innovation capabilities through channels such as improving the level of data asset information disclosure, reducing failure risks in the innovation process, and enhancing the activity of R&D systems. This reveals that eco-compensation policies not only serve as resource incentives but also provide crucial support for innovation by enhancing firms' internal information environments and organizational knowledge bases. The heterogeneity analysis shows that the policy effects are more pronounced in regions where big data management institutions have not yet been reformed, where data element utilization is low, and where industry–academia–research collaboration is lacking.

7.2. Policy recommendations

Drawing on the findings of this study, the following policy recommendations are put forward: First, it is imperative to refine the design of eco-compensation policies and bolster differentiated incentive mechanisms. In regions where big data management institutions remain unreformed or institutional support is lacking, fiscal transfer payments and compensation criteria should be augmented to enhance the targeting and precision of policy incentives, thereby fostering stronger expectations for innovation-driven incentives. At the same time, compensation methods and assessment indicators should be flexibly adjusted according to differences in enterprises' resource endowments and innovation foundations to avoid a "one-size-fits-all" policy design and improve the policy's adaptability and effectiveness. Second, improve the construction of data element markets to stimulate the innovative potential of enterprise data resources. The government should further promote the construction of a system for the confirmation of data asset rights, transactions, and circulation, reduce institutional barriers to the use of data elements, and guide enterprises to enhance their data management and utilization capabilities. For enterprises with low levels of data element utilization, technical training, support for standard setting, and demonstration projects can be provided to improve their basic conditions for data-enabled innovation, thereby enhancing the endogenous response capacity of policy incentives. Third, strengthen the construction of industry-academia-research collaborative innovation systems to address shortcomings in enterprise innovation resources. For enterprises that lack a foundation for cooperative innovation, measures such as establishing joint R&D funds, supporting the construction of industry-university-research platforms, and providing tax incentives should be taken to encourage enterprises to establish closer cooperative relationships with universities, research institutes, and other innovation entities, enhance the external knowledge spillover effect, and strengthen the sustainability and systematic nature of breakthrough innovation in enterprises. Finally, attention should be paid to the dynamic assessment and adjustment of policies to enhance the sustainability of the eco-compensation mechanism. Government departments should establish a regular monitoring and evaluation system for policy implementation outcomes, combining enterprise innovation behavior, regional environmental improvements, and changes in economic benefits to dynamically optimize the combination of eco-compensation policy tools, ensuring the sustained release of policy effects and the continuous improvement of innovation incentive mechanisms.

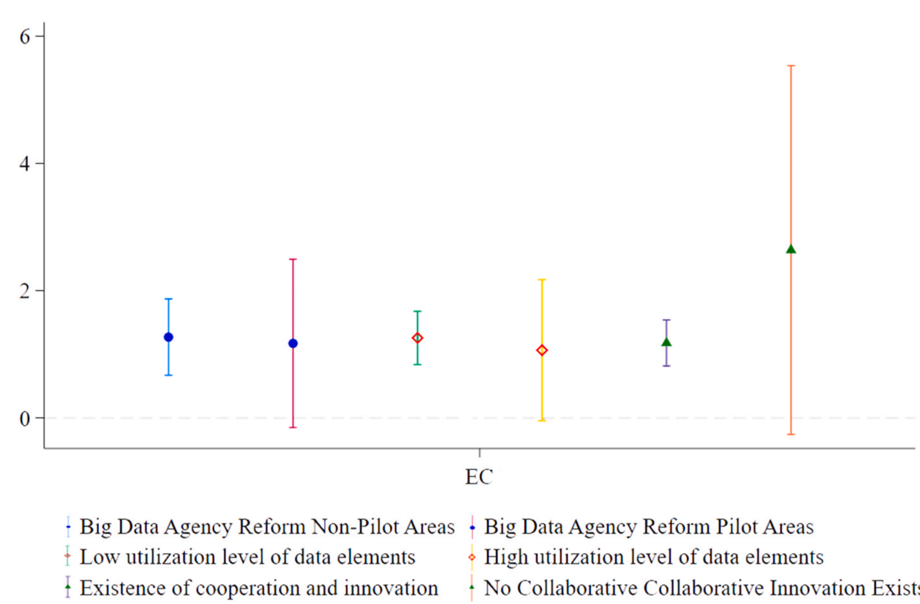

Fig. 4. Visualization of heterogeneity.

7.3. Limitations and future research directions

Although this paper conducts a systematic study on the impact of eco-compensation policies on breakthrough innovation in heavily polluting enterprises, and draws a series of important findings with theoretical significance and practical value, there are still several shortcomings that need to be further explored and improved in future research. This paper focuses on three mechanism variables data asset information disclosure, innovation risk, and R&D activity—to reveal the internal transmission logic of policy incentives. However, breakthrough innovation is a complex dynamic behavior that may be influenced by multiple factors, such as organizational learning ability, green supply chain collaboration, and financial constraint relief. Future research can construct a more comprehensive framework for identifying intermediary paths from a multi-level and multi-channel perspective to expand the theoretical and empirical exploration of the mechanism of action. Additionally, due to limitations in the time span of the data, this paper primarily focuses on the medium- and short-term innovation responses following policy implementation, while breakthrough innovation often exhibits long-term cumulative characteristics. Future research could utilize longer time series data and employ dynamic panel models to conduct in-depth analyses of the impact patterns of eco-compensation policies on enterprises' long-term green transformation and innovation evolution trajectories.

CRediT authorship contribution statement

Chao-Fan Chen: Writing – review & editing, Writing – original draft, Software, Resources, Project administration, Conceptualization. **Zixin Zhou:** Writing – original draft, Investigation, Formal analysis. **Chuan Li:** Writing – original draft, Methodology, Investigation, Data curation. **Wei Liu:** Writing – original draft, Supervision, Formal analysis, Data curation.

Declaration of competing interest

The authors have nothing to declare.

Data availability

Data will be made available on request.

References

Ahuja, G., Lampert, C.M., 2001. Entrepreneurship in the large corporation: a longitudinal study of how established firms create breakthrough inventions. Strateg. Manag. J. 22 (6-7), 52543.
Bi, X., Liu, S., Fu, S., Zhang, Y., 2022. Does earnings smoothing affect corporate breakthrough innovation? Evidence from external stakeholders' evaluation. Accounting Research (12), 91–102 (in Chinese).
Brännlund, R., Lundgren, T., 2009. Environmental policy without costs? A review of the porter hypothesis. International Review of Environmental and Resource Economics 3 (2), 75–117.
Byun, S.K., Oh, J.M., Xia, H., 2021. Incremental vs. breakthrough innovation: the role of technology spillovers. Manag. Sci. 67 (3), 1779–1802.
Cao, H., Li, M., Qin, F., Xu, Y., Zhang, L., Zhang, Z., 2022. Economic development, fiscal ecological compensation, and ecological environment quality. Int. J. Environ. Res. Publ. Health 19 (8), 4725.
Cao, H., Qi, Y., Chen, J., Shao, S., Lin, S., 2021. Incentive and coordination: ecological fiscal transfers' effects on eco-environmental quality. Environ. Impact Assess. Rev. 87, 106518.
Datta, A.A., Srivastava, S., 2023. (Re) conceptualizing technological breakthrough innovation: a systematic review of the literature and proposed framework. Technol. Forecast. Soc. Change 194, 122740.
Du, K., Cheng, Y., Yao, X., 2021. Environmental regulation, green technology innovation, and industrial structure upgrading: the road to the green transformation of Chinese cities. Energy Econ. 98, 105247.
Ferreira, J.J., Fernandes, C.I., Veiga, P.M., Dooley, L., 2023. The effects of entrepreneurial ecosystems, knowledge management capabilities, and knowledge spillovers on international open innovation. R D Manag. 53 (2), 322–338.
Gao, Q., Cheng, C., Sun, G., 2023. Big data application, factor allocation, and green innovation in Chinese manufacturing enterprises. Technol. Forecast. Soc. Change 192, 122567.
Gao, Z., Zhao, Y., Li, L., Hao, Y., 2025. How does supply chain digitalization enhance energy resilience? Empirical evidence from listed companies in China. Energy Econ. 145, 108447.
González-Piñero, M., Páez-Avilés, C., Juanola-Feliu, E., Samitier, J., 2021. Cross-fertilization of knowledge and technologies in collaborative research projects. J. Knowl. Manag. 25 (11), 34–59.
Guan, Q., Li, H., Guan, C., Chen, J., Fan, Y., 2024. Identification of ecological compensation zones and compensation amounts: a case study of the Yellow River Delta. Land 13 (10), 1582.
Hadlock, C.J., Pierce, J.R., 2010. New Evidence on Measuring Financial Constraints: Moving Beyond the KZ Index.
Hsu, C.C., Quang-Thanh, N., Chien, F., Li, L., Mohsin, M., 2021. Evaluating green innovation and performance of financial development: mediating concerns of environmental regulation. Environ. Sci. Pollut. Control Ser. 28 (40), 57386–57397.
Hu, G., Wang, X., Wang, Y., 2021. Can the green credit policy stimulate green innovation in heavily polluting enterprises? Evidence from a quasi-natural experiment in China. Energy Econ. 98, 105134.
Hu, H., Tian, G., Wu, Z., Xia, Q., 2023. Cross-regional ecological compensation under the composite index of water quality and quantity: a case study of the Yellow River Basin. Environ. Res. 238, 117152.
Hu, S., Gong, H., Li, S., 2024. Fail forward: the relationship between innovation failure and breakthrough innovation in the context of knowledge-based capabilities. Eur. J. Innovat. Manag.
Hunjra, A.I., Zhao, S., Tan, Y., Bouri, E., Liu, X., 2024. How do green innovations promote regional green total factor productivity? Multidimensional analysis of heterogeneity, spatiality and nonlinearity. J. Clean. Prod. 467, 142935.
Kraus, S., Vonmetz, K., Orlandi, L.B., Zardini, A., Rossignoli, C., 2023. Digital entrepreneurship: the role of entrepreneurial orientation and digitalization for disruptive innovation. Technol. Forecast. Soc. Change 193, 122638.
Kyaw, K., 2022. Effect of policy uncertainty on environmental innovation. J. Clean. Prod. 363, 132645.
Li, H., Du, G., Qamri, G.M., Li, S., 2024. Green innovation and natural resource efficiency: the role of environmental regulations and resource endowment in Chinese cities. J. Environ. Manag. 370, 122338.
Li, J., Qamri, G.M., Tang, M., Cheng, Y., 2025. Connecting the sustainability: how renewable energy and digitalization drive green global value chains. J. Environ. Manag. 380, 124779.
Liu, X., Liu, J., Afthanorhan, A., Hao, Y., 2024. Heating up the divide: climate change and the quest for inclusive growth in urban China. J. Environ. Manag. 369, 122269.
Lyu, S., Niu, S., Yuan, J., Zhan, Z., 2024. Developing professional capital through technology-enabled university-school-enterprise collaboration: an innovative model for C-STEAM preservice teacher education in the Greater Bay area. Asia Pac. J. Innov. Entrep. 18 (3), 270–299.
Ma, L., Iqbal, N., Bouri, E., Zhang, Y., 2023. How good is green finance for green innovation? Evidence from the Chinese high-carbon sector. Resour. Policy 85, 104047.
Ni, L., Ahmad, S.F., Alshammari, T.O., Liang, H., Alsanie, G., Irshad, M., et al., 2023. The role of environmental regulation and green human capital towards sustainable development: the mediating role of green innovation and industry upgradation. J. Clean. Prod. 421, 138497.
Niu, B., Yu, X., Yuan, Z., Chen, L., 2024. Data asset information disclosure and auditors' pricing strategies. Contemp. Finance Econ. (2), 154–164 (in Chinese).
Pedersen, E.R.G., Lüdeke-Freund, F., Henriques, I., Seitanidi, M.M., 2021. Toward collaborative cross-sector business models for sustainability. Bus. Soc. 60 (5), 1039–1058.
Porter, M.E., 1991. Towards a dynamic theory of strategy. Strateg. Manag. J. 12 (S2), 95–117.
Qamri, G.M., Sheng, B., Adeel-Farooq, R.M., Alam, G.M., 2022. The criticality of FDI in environmental degradation through financial development and economic growth: implications for promoting the green sector. Resour. Policy 78, 102765.
Qamri, G.M., Bin, S., Sanchuan, L., Hui, G., 2025. Unveiling sustainable mineral resources extraction, foreign direct investment, technology advancement nexus: evidence from BRICS countries. Resour. Policy 100, 105428.
Rafik, S., 2022. Innovation in times of crisis: a systematic literature review. Вестник Санкт-Петербургского униθерситета. МенедЖМент 21 (3), 429–471.
Sendstad, L.H., Chronopoulos, M., Hagspiel, V., 2021. Optimal risk adoption and capacity investment in technological innovations. IEEE Trans. Eng. Manag. 70 (2), 576–589.
Shang, W., Gong, Y., Wang, Z., Stewardson, M.J., 2018. Eco-compensation in China: theory, practices and suggestions for the future. J. Environ. Manag. 210, 162–170.
Shao, Y., Xu, K., 2024. Be cautious or win in danger? Firms' economic policy uncertainty perception and green technology innovation. Asia Pacific. J. Manag. 1–33.
Shen, J., Gao, X., He, W., Sun, F., Zhang, Z., Kong, Y., et al., 2021. Prospect theory in an evolutionary game: construction of watershed ecological compensation system in Taihu Lake Basin. J. Clean. Prod. 291, 125929.
Shi, Q., Niu, Y., Xu, H., 2023. Mechanisms through which the utilization level of data elements affects investment efficiency: the mediating role of redundant resource activation. J. Cent. Univ. Finance Econ. (11), 105–115 (in Chinese).
Verhoeven, D., Kovacs, A., Marullo, C., Di Minin, A., Van Looy, B., 2025. More or the same? Radical, disruptive, discontinuous, and breakthrough innovation. Ind. Corp. Change, dtae045.

Wang, Y., Feng, J., Shinwari, R., Bouri, E., 2024. Do green finance and green innovation affect corporate credit rating performance? Evidence from machine learning approach. J. Environ. Manag. 360, 121212.
Wang, Y., Luo, N., Liu, W., 2019. What kind of leverage is conducive to enterprise innovation? China Industrial Economics (3), 138–155 (in Chinese).
Wu, H., Hao, Y., Ren, S., 2020. How do environmental regulation and environmental decentralization affect green total factor energy efficiency: evidence from China. Energy Econ. 91, 104880.
Wu, H., Luo, S., Li, S., Xue, Y., Hao, Y., 2024. Fostering urban inclusive green growth: does corporate social responsibility (CSR) matter? J. Bus. Ethics 189 (4), 677–698.
Xiang, H., Chen, J., Wu, F., 2024. Patent insurance pilot policy and enterprise digital transformation. Insurance Studies (3), 31–47 (in Chinese).
Xu, X., 2021. Research prospect: data factor of production. Journal of Internet and Digital Economics 1 (1), 64–71.
Xue, J., Lang, J., Guan, Y., Lu, S., 2023. Design and measurement of small-scale regional ecological compensation model. Econ. Anal. Pol. 78, 1392–1405.
Yang, X., Zhang, P., Hu, X., Qamri, G.M., 2024. Environmental pollution and officials' promotion: how China's green attention matters. J. Environ. Manag. 365, 121590.
Ye, F., Paulson, N., Khanna, M., 2024. Strategic innovation and technology adoption under technological uncertainty. J. Econ. Dynam. Control 165, 104879.
Yu, B., Liu, H., Cheng, H., Gao, P., 2022. The impact of cross-border knowledge management on internationalizing Renminbi: lessons from the belt and road initiative. J. Knowl. Manag. 26 (1), 257–267.
Zhong, X., Ren, G., Wu, X., 2025. Not all innovation is prioritized: economic policy uncertainty, industry environmental, and firms' relative exploitative innovation emphasis. Eur. J. Innovat. Manag. 28 (2), 166–186.
Zhou, Y., Luo, H., Tang, J., Zhang, L., Zhu, H., Sun, S., 2023. Study on ecological environment damage compensation in China. J. Nat. Conserv. 76, 126503.
Zhu, W., Han, W., Lu, R., Lei, J., 2025. The impact of enterprises' scientific capabilities on innovation performance: evidence from an empirical analysis and simulation model. Humanit. Soc. Sci. Commun. 12 (1), 1–18.