

Article

The Dual Impacting Effects of Government Environmental Policies and Corporate Pollution Levels on Corporate R&D Investment

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Abstract

Against the backdrop of increasingly severe global environmental issues, the manner in which enterprises conduct R&D investment, influenced by both government environmental policies and their own pollution levels, has become a prominent research topic. This paper employs the bilateral random frontier model of information game (SFA2tier) to analyze the influence levels and determining factors of government and market enterprises. The findings reveal that enterprises exert a stronger influence than the government, with the latter able to enhance R&D investment by 5.50% through its own influence. The disparity in influence levels between government and enterprises regarding R&D investment is significant and varies according to regional economic development levels and administrative hierarchies. Key determining factors include government subsidies, the nature of enterprise ownership, and enterprise size. The research results not only enrich relevant theories concerning the relationship between environmental policies and enterprise R&D investment but also provide valuable insights for the government to formulate more effective environmental policies and for enterprises to develop R&D strategies.

Keywords: information asymmetry; enterprise R&D investment; bilateral random frontier model; environmental policy; enterprise pollution level



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1. Introduction

With increasingly severe global environmental challenges, such as climate change, resource depletion, and environmental pollution, countries are confronted with significant obstacles. In response, governments worldwide have intensified environmental regulations and promoted green transformations [1]. The Chinese government has set forth the “dual carbon” goal, which aims to achieve peak carbon emissions before 2030 and carbon neutrality by 2060. Shahbaz et al. (2021) state that the construction of the ecological environment is closely linked to the future growth potential of the economy, making the coordination of harmonious development between the two an important issue for countries seeking sustainable economic development models in recent years [2]. According to the “2018 Development Report on China’s Economic Ecological Gross Domestic Product Accounting,” released by the Environmental Planning Institute of the Ministry of Ecology and Environment of China, the cost of environmental pollution in 2015 amounted to CNY 2 trillion, while the cost associated with ecological damage reached CNY 0.63 trillion.

The “2024 China Ecological Environment Status Bulletin” further indicates that, in 2024, the quality of the national ecological environment will continue to improve, the environmental security situation will remain stable, and public satisfaction with the ecological environment will exceed 90% for the fourth consecutive year. However, the effectiveness of improving ecological environmental quality remains insufficiently stable, and the challenges associated with such improvements are expected to increase. Based on relevant data from the Global Timely Carbon Data Platform, this article presents the following chart, which illustrates that China’s carbon emissions continued to rise from 2019 to 2024, exhibiting significant sectoral differences. Under the government’s robust environmental monitoring mechanism, the growth rate of carbon emissions from 2023 to 2024 slowed down (Figure 1).

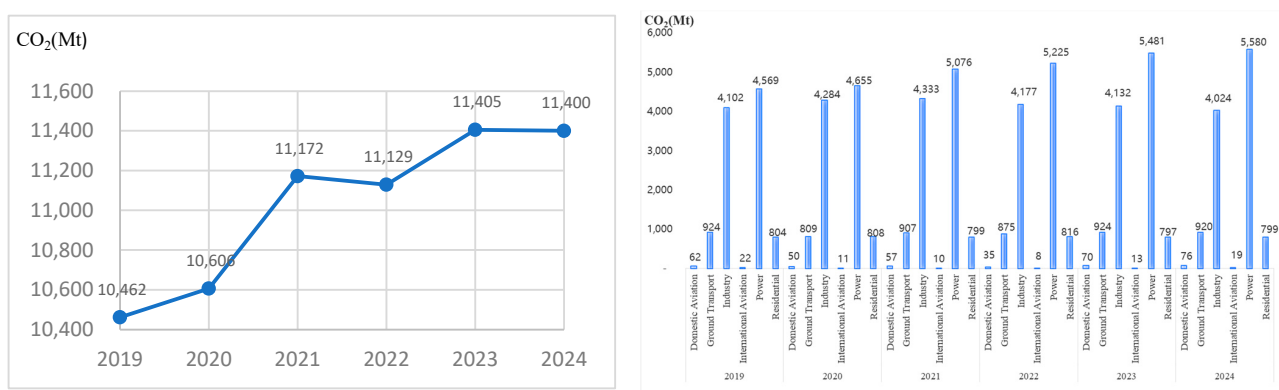


Figure 1. China’s total carbon emissions and the classified carbon emissions of six sectors.

This objective necessitates urgent industrial restructuring. In this context, enterprises, as the primary agents of economic activities, face substantial policy pressures. Environmental policies—including emission standards, carbon trading mechanisms, and environmental taxes—have notably increased compliance costs for enterprises, particularly in high-polluting industries. These policies not only impact the economic performance of enterprises but may also influence their selection of technological innovation paths through incentive or constraint mechanisms. Notably, significant disparities in pollution emission levels exist among different enterprises, attributable to factors such as industry characteristics, technological capabilities, and regional distribution [3]. Consequently, the sensitivity and response strategies of enterprises to environmental policies exhibit a differentiated trend.

At the theoretical level, a debate persists between the Porter hypothesis and cost theory regarding the influence of environmental regulations on corporate innovation. The Porter hypothesis posits that stringent environmental policies can stimulate corporate research and development through innovation compensation effects, thereby enhancing competitiveness [4]. Conversely, opposing viewpoints argue that environmental policies may constrain R&D resources, escalate compliance costs, and subsequently inhibit innovation capabilities. Most existing research has concentrated on the unidirectional effects of environmental policies on corporate innovation, overlooking the moderating role of corporate pollution heterogeneity in this relationship. Furthermore, there remains a lack of investigation into the driving factors that lead enterprises to choose between “passive response” and “active change” under policy pressures. Particularly in the context of China, factors such as the intensity of policy implementation and industry heterogeneity may confound research conclusions, necessitating further theoretical and empirical analysis [5].

This study aims to construct an integrated analytical framework for examining the relationships among policy pressure, enterprise pollution levels, and research and devel-

opment behaviors. It reveals the dual interactive effects between environmental policies and enterprise characteristics. This framework not only deepens the understanding of the boundary conditions relevant to Porter's hypothesis but also provides a theoretical foundation for governments to design differentiated environmental policies. Practically, the findings can guide governments in formulating more effective environmental policies, thereby avoiding the inefficiencies or negative impacts associated with a "one-size-fits-all" approach. Simultaneously, this study can assist enterprises in developing innovative strategies tailored to their specific pollution levels, encouraging high-pollution enterprises to transition from passive governance to active technological innovation, thereby achieving the coordinated development of environmental and economic performance.

China's environmental regulations exhibit dynamic characteristics, manifesting as the parallel evolution of "dynamic governance" and "long-term mechanism construction". The uncertainty inherent in this policy environment presents challenges for businesses. Additionally, there exists a significant imbalance between regions and industries within China. While environmental standards in the eastern coastal areas are relatively stringent, the central and western regions may relax regulations during the industrial transfer process. There are also considerable differences in pollution control requirements between traditional heavy industries and emerging industries. In the context of transitioning from high-speed economic growth to high-quality development, Chinese enterprises urgently need to overcome the "environmental cost" dilemma through green innovation to achieve sustainable development. Therefore, this study will pay particular attention to the unique context of China, aiming to provide more targeted recommendations for policy formulation and corporate practices.

As the primary driving force behind technological innovation, R&D investment levels vary depending on the specific conditions of the company and the prevailing government environmental policies. Consequently, the influence of government and market forces on R&D investment may differ in time and space due to varying stages of economic development and administrative regions, indicating heterogeneity. To achieve this objective, this article utilizes the China Industrial Enterprise Database and the China Industrial Enterprise Pollution Database to match data and employs a bilateral stochastic frontier model of information game (SFA2tier) to estimate and test the degree of information asymmetry and its determinants between government and market enterprises regarding R&D investment across different economic development stages and administrative regions. This study aims to provide a decision-making basis for enhancing China's scientific and technological innovation capabilities, revealing the heterogeneity of information asymmetry between the government and enterprises in R&D investment and its underlying causes. The potential contributions of this article include the following: (1) applying the benchmark information game model to analyze the formation mechanism of R&D investment, establishing hypotheses regarding surplus conditions for R&D investment to measure the influence of government and market enterprises, and proposing a mechanism for allocating R&D investment surpluses; (2) utilizing the bilateral stochastic frontier model (SFA2tier) to measure the impacts of government and enterprises on R&D investment using micro-level individual characteristic data; and (3) comparing and analyzing different stages of economic development and administrative regions to unveil the heterogeneity of the impacts of government and market enterprises on R&D investment and their decisive factors.

2. Theoretical Basis and Research Hypotheses

2.1. Government Environmental Policy Constraints and Enterprise R&D Investment (From the Perspective of the Government)

Research and development investment motivated by government subsidies: Government subsidies mainly play a role in incentivizing companies to raise the funds needed for innovative investments. Relevant studies have shown that government subsidies to companies' research and development activities can have a stimulating effect and may also lead to crowding-out effects [6]. A summary of the existing literature reveals that most studies believe government subsidies can effectively stimulate companies to invest funds in research and development activities [7]. However, due to restrictions on the availability of micro-level data, the results of such studies still have certain limitations.

Some of the literature has conducted in-depth research into both the ways that government subsidies incentivize enterprise R&D motivation and their effects. Representative views include that managers' decision-making behavior often exhibits short-term characteristics, and although government subsidies can promote R&D investment, their incentive effect is relatively weak [8]; the promotion effect of government subsidies on R&D activities from the perspective of capital cost, pointing out that government subsidies can provide operational funds for enterprises at a lower cost [9]; and empirical research based on data from SMEs listed on the SME board shows that government R&D subsidies overall have a promoting effect on enterprise R&D investment [10].

The enterprises obtaining government subsidies through false information weaken the incentive effect. Neither direct nor indirect support from the government is conducive to improving R&D innovation efficiency. Direct subsidies for R&D activities by the government and the deduction and remission subsidies for enterprise R&D activities are negatively correlated with R&D efficiency. Ownership differences exist in the impact of government subsidies on enterprise R&D investment, with state-owned enterprises having a lower R&D incentive effect than private enterprises [11].

The impact of government subsidies on firms' R&D investment: The existing literature generally suggests that government subsidies have two distinct effects on firms' R&D investment, namely the incentive effect brought by identity recognition and the restraint effect caused by rent-seeking behavior [12,13]. However, the relative strength of these two effects varies with the scale of the government subsidies, resulting in different impacts of government subsidies on firms' R&D investment [14]. When the scale of government subsidies is within a certain range, it can help firms share the risks of innovation failures [15] and reduce firms' financing costs and the uncertainty of R&D risks, thereby prompting firms to increase their R&D investment [16,17]. This mechanism effectively attracts additional investment in firms' R&D from external investors, alleviating the financing constraints faced by firms in their R&D activities [18].

2.2. The Relationship Between the Level of Pollution and the R&D Investment of Enterprises (From the Perspective of the Enterprises)

The existing literature has focused on the relationship between market competition and R&D investment, but the research conclusions are not consistent. There is a significant positive relationship between market competition intensity and R&D investment [19]. Scholars have argued that there is an inverted U-shaped relationship between the level of market competition faced by enterprises and their technological innovation behavior [20]. In domestic research, in highly competitive product markets, the intensity of R&D investment has not been shown to significantly improve innovation performance. Li et al. [21] used signal theory to explore the relationship among market competition, government resource allocation, and enterprise R&D investment. Bianchini et al. [22] treated market

competition as a moderating variable and studied the relationship between institutional investor stock holdings and enterprise R&D investment.

The impact of corporate pollution levels on R&D investment: The development of high-level theories has raised academia's attention to the influence of management characteristics on investment [23]. The heterogeneity of executive age can positively moderate the relationship between R&D investment and firm performance, while the heterogeneity of education level has a negative moderating effect [24]. Further research by a number of scholars has found the influence of management compensation and shareholding on R&D investment is subject to enterprise heterogeneity regulation; implementing management compensation incentives helps to enhance the promoting effect of R&D investment on corporate financial performance, and product market competition has a moderating effect on this relationship [25–27].

2.3. Research Hypothesis

Currently, most scholars have conducted research on the influencing factors of R&D investment, including government tax incentives [28], subsidies [29], funding [30], environmental policies [31], property rights protection [32], corporate governance [33], corporate size [34], political connections, and government-enterprise relations [35], as well as external factors such as utilization of foreign investment [36,37], financing constraints [38], and geographical environment [39,40]. Although [41] explored the impact of government departments and corporate attributes on R&D investment based on panel data analysis models, they were unable to fully objectively reveal the impact of R&D entities in the formation process of R&D investment under information asymmetry conditions due to their narrow selection of regions or macro data [31]. Generally, the difference between the actual R&D investment and the minimum R&D investment that the government can accept forms “government surplus”, while the difference between the highest R&D investment that an enterprise can pay and the actual R&D investment forms “enterprise surplus” [28]. The surplus obtained is used to measure the influence of governments and market businesses. A lack of information exchange between government departments and market enterprises can lead to inefficient R&D investment. Excessive R&D investment in the short term can increase production costs and risks for enterprises, thereby dampening their enthusiasm for R&D investment and causing some enterprises to withdraw from the market. This information asymmetry has resulted in a low level of R&D investment in China, which has severely harmed China's capacity for scientific and technological innovation [36,37]. Long-term and short-term effects of information asymmetry on the efficacy of China's R&D investments are evident. Therefore, the first research hypotheses are proposed:

Hypothesis 1a. *Information asymmetry will affect China's R&D investment through government departments.*

Hypothesis 1b. *Information asymmetry will affect China's R&D investment through enterprises.*

R&D investment is the most direct driving force for scientific and technological innovation [42]. Nonetheless, there may be distinctions in information efficiency between regions with varying levels of economic development, resulting in a relatively efficient market. In addition, provincial capital cities are often the birthplace and gathering center of information resources in China. It can be seen that the impact of government and market enterprises on R&D investment in administrative districts at different economic developmental stages may not only vary over time, but also in spatial heterogeneity. Qi et al. [43] analyzed the moderating effect of government policies and corporate characteristics on R&D investment. However, due to the lack of representativeness or limited coverage of

the panel data they selected, they were unable to fully and objectively reveal the heterogeneity of R&D entities in the formation process of R&D investment under information asymmetry conditions. It should be particularly pointed out that enterprises use the market information obtained to determine the scale of R&D investment and maximize profits [38]. Then this heterogeneous macro policy introduces information bias into the implementation process, which will inevitably lead to information asymmetry in the formation mechanisms of R&D investment. Therefore, the second research hypothesis proposed is

Hypothesis 2. *There is regional heterogeneity in the impact of information asymmetry on China's R&D investment.*

Domestic and international academicians investigate the factors influencing enterprise R&D investment from the perspectives of government funding and corporate characteristics, including the asset–liability ratio, industry, development, and performance [34,44]. In terms of government subsidies, the government spends a large amount of public funds and implements policy advantages such as interest subsidies, loan guarantees, and R&D subsidies to alleviate the debt-and-equity gap in enterprise innovation projects [45]. In terms of enterprise size, Schumpeter emphasizes that the resource endowment possessed by a sufficiently large-scale enterprise is the basic condition for innovation from the characteristics of innovation resource demand [46]. Enterprises in a period of high return are unwilling to adopt high-risk behaviors by decision-makers, whereas enterprises in a period of low return are willing to adopt such behaviors by decision-makers. Numerous domestic and international studies have also demonstrated that political connections are prevalent in businesses and have a significant impact on their R&D expenditures [32].

Under the influence of motives such as obtaining a business license or economic rent, entrepreneurs will spend resources such as time and money to establish good relationships with the government [47]. Moreover, politically-affiliated enterprises can more easily obtain franchise licenses, thereby obtaining higher excess profits. Therefore, politically-affiliated enterprises will invest more resources in these government-regulated franchise projects with shorter investment payback periods in order to reduce their R&D investment [48]. Furthermore, politically-affiliated enterprises can receive more financial subsidies. In addition, multinational corporations can attract talent from host countries, build industry barriers, intensify market competition, and squeeze out R&D investment from local enterprises by leveraging their own financial advantages [48] (Figure 2). Therefore, the third research hypotheses are proposed:

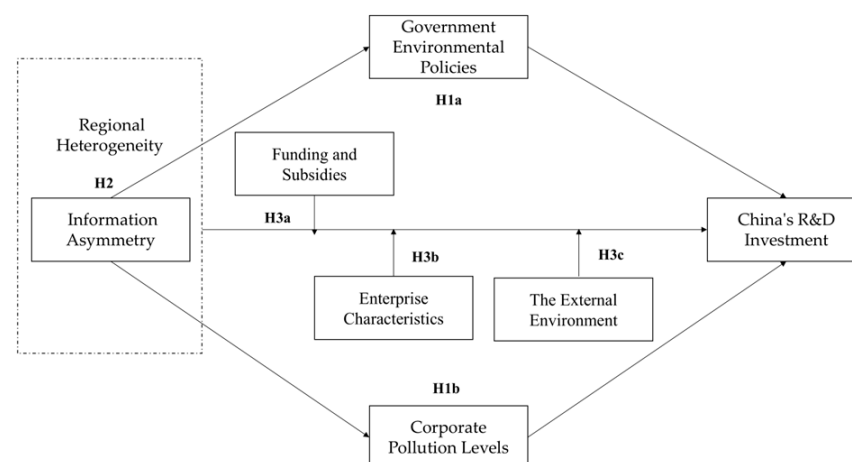


Figure 2. The theoretical mechanism.

Hypothesis 3a. *Funding and subsidies are the determinants of information asymmetry affecting China's R&D investment.*

Hypothesis 3b. *Enterprise characteristics are the determinants of information asymmetry affecting China's R&D investment.*

Hypothesis 3c. *The external environment is the determinant of information asymmetry affecting China's R&D investment.*

3. Methods

3.1. Logical Deduction and Model Setting

3.1.1. Benchmark Model for Remaining R&D Investment

Assuming that there is a mechanism for forming R&D investment, governments implement different environmental policies that require increased social R&D investment and clean production, and many enterprises can formulate corresponding R&D budgets based on their own information [49]. At this point, governments and market enterprises can facilitate a reasonable R&D investment (R), which may be stated as follows:

$$R = \underline{R} + \eta(\bar{R} - \underline{R}) \quad (1)$$

where $\underline{R}$ represents the minimum social R&D investment that the government expects to achieve in implementing environmental policies, and $\bar{R}$ represents the highest R&D investment that enterprises are willing to pay in obtaining market information. $\eta(0 \leq \eta \leq 1)$ indicates the influence of the government on R&D investment by market enterprises. Therefore, $\eta(\bar{R} - \underline{R})$ can be used to represent the surplus that governments can seize in achieving reasonable R&D investment by the government and market enterprises.

To reflect the influence of governments and market enterprises in the R&D investment process, Equation (1) is decomposed. According to the benchmark, R&D investment exists under the established basic characteristics x of the enterprise $\mu(x) = E(\theta|x)$, where θ objectively exists but cannot be fully understood in reality [23]. At the same time, it meets $\underline{R} \leq \mu(x) \leq \bar{R}$ and $\mu(x)$ is difficult to accurately estimate, but it objectively exists. At this point, $(\bar{R} - \mu(x))$ represents the expected surplus of the enterprise in the process of achieving R&D investment. $(\mu(x) - \underline{R})$ indicates the expected surplus of the government in the process of achieving R&D investment. However, the strength of the surplus R&D investment acquired by both the government and market enterprises depends on the influence possessed by both parties. Thus, Equation (1) can be decomposed into

$$\begin{aligned} R &= \mu(x) + [\underline{R} - \mu(x)] + \eta[\bar{R} - \mu(x)] - \eta[\underline{R} - \mu(x)] \\ &= \mu(x) + \eta[\bar{R} - \mu(x)] - (1 - \eta)[\mu(x) - \underline{R}] \end{aligned} \quad (2)$$

From Equation (2), it can be seen that governments can increase R&D investment by capturing the expected surplus of enterprises, and the captured surplus can be represented by $\eta[\bar{R} - \mu(x)]$. Similarly, market enterprises can reduce R&D investment by capturing the surplus of government expectations, and the surplus captured can be represented by $(1 - \eta)[\mu(x) - \underline{R}]$. At this point, the surplus that the government can seize mainly depends on the degree of government influence η and the expected surplus of enterprises $\bar{R} - \mu(x)$, while the surplus that market enterprises can seize mainly depends on the degree of enterprise influence $(1 - \eta)$ and the expected surplus of the government $\mu(x) - \underline{R}$. This means that governments can use their own influence to increase R&D investment, while enterprises can use their own influence to reduce R&D investment.

Equation (2) mainly consists of three parts, that is, “R&D = Benchmark R&D investment $\mu(x)$ + the surplus acquired by the governments under their influence $\eta[\bar{R} - \mu(x)]$ – Surplus obtained by market enterprises using the degree of influence $(1 - \eta)[\mu(x) - \underline{R}]$ ”. This study uses NS to represent net surplus, $NS = \eta[\bar{R} - \mu(x)] - (1 - \eta)[\mu(x) - \underline{R}]$. It is used to measure the comprehensive effect of the influence of both the government and market enterprises on the final R&D investment. When $NS > 0$, it indicates that the final R&D investment is higher than the benchmark R&D investment; when $NS < 0$, it indicates that the final R&D investment is less than the baseline R&D investment.

Under this analytical framework, we can see that the impact of R&D investment is bidirectional, with both positive and negative effects. Therefore, Equation (2) can be rewritten as follows:

$$R_i = \mu(x) + \xi_i, \quad \xi_i = w_i - u_i + v_i \quad (3)$$

Thus, the above model (3) is SFA2tier [24]. Where $\mu(x_i) = x_i'\beta$ represents the parameter vector to be estimated, and x_i represents the basic characteristics of the enterprise. β represents the vector of parameters to be estimated.

Where $w_i = \eta_i[\bar{R}_i - \mu(x_i)] \geq 0$; $u_i = (1 - \eta_i)[\underline{R}_i - \mu(x_i)] \geq 0$, v_i represents a random perturbation term, and w_i and u_i respectively, represent the expected remaining portion obtained by the government from enterprises and the expected remaining portion obtained by enterprises from the government. The size of these residuals is determined by the respective degrees of influence of the government and market enterprises, the expected residuals of enterprises, and the expected residuals of the government.

3.1.2. Estimation Method for Remaining R&D Investment

In order to estimate the surplus and parameters acquired by both the government and enterprises, the Maximum Likelihood Estimation (MLE) method is selected for estimation. The study assumes w_i and u_i ; that X follows an exponential distribution; v_i obeys a normal distribution; w_i , u_i , and v_i are mutually independent; and the composite disturbance term ξ_i is the probability density function. The function of w_i and u_i are $w_i = \eta_i[\bar{R}_i - \mu(x_i)] \geq 0$ and $u_i = (1 - \eta_i)[\underline{R}_i - \mu(x_i)] \geq 0$; where v_i represents a random perturbation term; and w_i and u_i , respectively, represent the expected remaining portion obtained by the government from enterprises and the expected remaining portion obtained by enterprises from the government. The size of these residuals is determined by the respective degrees of influence of the government and market enterprises, the expected residuals of enterprises, and the expected residuals of the government.

$$f(\xi_i) = \frac{\exp(a_i)}{\sigma_u + \sigma_w} \Phi(c_i) + \frac{\exp(b_i)}{\sigma_u + \sigma_w} \int_{-h_i}^{\infty} \psi(z) dz = \frac{\exp(a_i)}{\sigma_u + \sigma_w} \Phi(c_i) + \frac{\exp(b_i)}{\sigma_u + \sigma_w} \psi(h_i) \quad (4)$$

For the above model, $\psi(\cdot)$ and $\Phi(\cdot)$ represent the standard normal distribution probability density function and cumulative distribution function, respectively, and the other parameters are set as follows [8]:

$$a_i = \frac{\sigma_v^2}{2\sigma_u^2} + \frac{\xi_i}{\sigma_u}; \quad b_i = \frac{\sigma_v^2}{2\sigma_w^2} - \frac{\xi_i}{\sigma_w}; \quad h_i = \frac{\xi_i}{\sigma_v} - \frac{\sigma_v}{\sigma_w}; \quad c_i = -\frac{\xi_i}{\sigma_v} - \frac{\sigma_v}{\sigma_u}$$

For an individual datum containing N observations, the logarithmic likelihood function can be expressed as follows:

$$\ln L(x; \theta) = -n \ln(\sigma_u + \sigma_w) + \sum_{i=1}^n \ln[e^{a_i} \Phi(c_i) + e^{b_i} \psi(h_i)] \quad (5)$$

where $\theta = [\beta, \sigma_v, \sigma_u, \sigma_w]$, and maximizing the logarithmic likelihood function allows for estimating the maximum likelihood estimate of the parameter.

3.1.3. Deduction of the Residual R&D Investment for Both Government and Enterprises

For the surplus obtained by the government and enterprises in this article, the conditional distributions of u_i and w_i are derived, denoted as $f(u_i|\xi_i)$ and $f(w_i|\xi_i)$:

$$f(u_i|\xi_i) = \frac{\lambda \exp(-\lambda u_i) \Phi(u_i/\sigma_v + h_i)}{\Phi(h_i) + \exp(a_i - b_i) \Phi(c_i)} \quad (6)$$

$$f(w_i|\xi_i) = \frac{\lambda \exp(-\lambda w_i) \Phi(w_i/\sigma_v + c_i)}{\exp(b_i - a_i) [\Phi(h_i) + \exp(a_i - b_i) \Phi(c_i)]} \quad (7)$$

where $\lambda = 1/\sigma_u + 1/\sigma_w$. Furthermore, based on Equations (6) and (7), the conditional expectations for the random perturbation terms X and Y in the process of R&D investment formation can be obtained, expressed as follows:

$$E(1 - e^{-u_i}|\xi_i) = 1 - \frac{\lambda}{1 + \lambda} \frac{[\Phi(h_i) + \exp(a_i - b_i) \exp(\sigma_v^2/2 - \sigma_v c_i) \Phi(c_i - \sigma_v)]}{\Phi(h_i) + \exp(a_i - b_i) \Phi(c_i)} \quad (8)$$

$$E(1 - e^{-w_i}|\xi_i) = 1 - \frac{\lambda}{1 + \lambda} \frac{[\Phi(c_i) + \exp(b_i - a_i) \exp(\sigma_v^2/2 - \sigma_v h_i) \Phi(h_i - \sigma_v)]}{\exp(b_i - a_i) [\Phi(h_i) + \exp(a_i - b_i) \Phi(c_i)]} \quad (9)$$

At this point, the net surplus NS of both the government and market enterprises can be expressed as follows:

$$NS = E(1 - e^{-w_i}|\xi_i) - E(1 - e^{-u_i}|\xi_i) = E(e^{-u_i} - e^{-w_i}|\xi_i) \quad (10)$$

When estimating parameters, there is no need to assume in advance the relative degree of influence between the government and market enterprises. This can be determined by the estimated results, which is more advantageous compared to traditional regression analysis methods.

3.1.4. Government and Business Jointly Establish the Model for Obtaining the Remaining R&D Investment

This paper employs the OLS model, the government and business bilateral random frontier model, and the bilateral random frontier model without constraints for regression estimation. The OLS model 1, the bilateral stochastic frontier model 2 under constraint conditions, and the bilateral stochastic frontier model 3 without constraints are as follows:

Model 1:

$$\ln rand = \beta_0 + \beta_1 \times \ln age + \beta_2 \times pollution + \beta_3 \times will + \beta_4 \times subordination + \beta_5 \times subsidy + \beta_6 \times type + \beta_7 \times size + \beta_8 \times foreign + \beta_9 \times tax + v_i$$

Model 2:

$$\ln rand = \beta_0 + \beta_1 \times \ln age + \beta_2 \times pollution + \beta_3 \times will + \beta_4 \times subordination + \beta_5 \times subsidy + \beta_6 \times type + \beta_7 \times size + \beta_8 \times foreign + \beta_9 \times tax + w_i - u_i + v_i$$

Among them, the constraint conditions are $\ln \sigma_u = \ln \sigma_w = 0$.

Model 3:

$$\ln rand = \beta_0 + \beta_1 \times \ln age + \beta_2 \times pollution + \beta_3 \times will + \beta_4 \times subordination + \beta_5 \times subsidy + \beta_6 \times type + \beta_7 \times size + \beta_8 \times foreign + \beta_9 \times tax + \Sigma year + \Sigma area + w_i - u_i + v_i$$

The regression coefficient is $\beta_0 \sim \beta_9$, and $\sum year$ and $\sum area$ refer to the time factor and the regional factor, respectively.

3.2. Variable Selection and Data Sources

3.2.1. Variable Selection

In measuring the R&D investment of market enterprises, this article selects the indicator of “research and development expenses” from the Chinese industrial enterprise database. The main enterprise characteristic variables for measuring “benchmark R&D investment” include the pollution level and R&D willingness of the enterprise, its affiliation, government subsidies, ownership nature, scale, age, foreign investments, and tax situation.

The level of enterprise pollution: This article divides enterprises into three categories based on their pollution intensity [50], namely light, moderate, and heavy, which in turn indicate that the larger the R&D investment of an enterprise, the more different the environmental policy constraints it reflects.

Enterprise R&D willingness: This article reflects whether an enterprise has a research and development inclination by examining whether the enterprise is equipped with clean production equipment for handling wastewater, emissions, and other pollutants. Enterprises with clean production equipment often have a greater willingness to engage in technological research and development.

Other variables: The basic characteristics of enterprises include affiliation, government subsidies, ownership nature, scale, age, use of foreign capital, and tax payment status. In addition, time and regional factors are also controlled. Enterprises are classified as being in the start-up phase (assigned a 1), growth phase (assigned a 2), or mature phase (assigned a 3). Enterprises with an employee count greater than or equal to 2000 are defined as large-scale enterprises, while those with fewer than 2000 employees are defined as small-scale enterprises [51]. Enterprises with an annual tax payment exceeding or equal to CNY 1 million are defined as major tax contributors, while those with less than CNY 1 million are defined as minor tax contributors. The use of foreign capital is considered mainly due to higher production requirements for enterprises. The details of the variables can be found in Table 1.

Table 1. Distribution of samples.

Variables	Measure of Variable	Variable Name	Average	Standard Deviation	Minimum	Maximum
R&D expenses	R&D expenses invested by the enterprise (CNY thousands)	rand	8258.45	51,962.90	1	1,937,374
Pollution level of the enterprise	Pollution level of the enterprise (mild pollution, moderate pollution, and severe pollution are assigned values of 1, 2, and 3, respectively)	pollution	2.15	0.80	1	3
R&D willingness of the enterprise	Whether they use clean production equipment for treatment (1 for waste gas, wastewater, and other treatment equipment; 0 without waste gas, wastewater, or other treatment equipment)	will	0.71	0.46	0	1

Table 1. Cont.

Variables	Measure of Variable	Variable Name	Average	Standard Deviation	Minimum	Maximum
Basic characteristics of the enterprise						
Subordination	(1 for central or provincial, 0 other)	subordination	0.21	0.39	0	1
Government subsidies	(1 with subsidies, 0 without subsidies)	subsidy	0.37	0.48	0	1
Ownership	(1 state-owned, 0 non-state-owned)	type	0.23	0.42	0	1
Enterprise size	(1 large-scale, 0 small-scale)	size	0.12	0.32	0	1
Age	(Number of years of existence of the enterprise, rounded as an integer)	age	19.54	19.19	1	408
Foreign-funded enterprise	(1 foreign-funded enterprise, 0 non-foreign-funded enterprise)	foreign	0.15	0.36	0	1
Major taxpayer	(1 yes, 0 no)	tax	0.23	0.41	0	1
Control variables						
Time factor	Survey year (four years)	year	-	-	-	-
Regional factors	Surveyed regions (divided into eastern, central, and western regions by economic development; provincial and non-provincial capital cities by different administrative levels)	area	-	-	-	-

3.2.2. Data Sources

The China Industrial Enterprise Database and China Industrial Enterprise Pollution Emissions Database provided the data used in this study. Due to the fact that the R&D investment indicators in the database only covered four years—2005, 2006, 2007, and 2010—samples with missing, abnormal, or negative values were excluded, and the entire sample dataset was subjected to 1% tail reduction, resulting in a total of 21,770 samples of data. It encompassed 31 Chinese provinces (cities). From the perspective of regional division, 31 provinces (cities) in China were divided into the eastern region (12 provinces (cities) including Liaoning, Hebei, Tianjin, Beijing, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi, and Hainan), the central region (9 provinces including Heilongjiang, Jilin, Inner Mongolia, Shanxi, Anhui, Jiangxi, Henan, Hubei, and Hunan), and the western region (10 provinces (cities) including Shaanxi, Gansu, Ningxia, Qinghai, Xinjiang, Sichuan, Yunnan, Guizhou, Tibet, and Chongqing) based on the differences in economic development levels. According to the different administrative levels of the cities, the research areas were divided into provincial capital cities (Jinan, Shijiazhuang, Changchun, Harbin, Shenyang, Hohhot, Urumqi, Lanzhou, Yinchuan, Taiyuan, Xi'an, Zhengzhou, Hefei, Nanjing, Hangzhou, Fuzhou, Guangzhou, Nanchang, Haikou, Nanning, Guiyang, Changsha, Wuhan, Chengdu, Kunming, Lhasa, Xining, Tianjin, Shanghai, Chongqing, and Beijing) and non-provincial capital cities. The sample distribution can be found in Table 2. And in order

to clearly understand the sample distribution, this study distribute the sampling into three proportion charts of different divided regions or city types in Figure 3, the level of economic development in Figure 4 and proportion chart divided by different administrative levels in Figure 5.

Table 2. Sample distribution.

		Observed Samples	Proportion (%)	Ownership		Use of Foreign Capital		Government Subsidies	
				Non-State-Owned (%)	State-Owned (%)	Non-Foreign (%)	Foreign (%)	Unsubsidized (%)	Subsidized (%)
According to the level of economic development	Eastern region	13,323	61.2	49.86	11.34	49.07	12.13	38.87	22.33
	Central region	4152	19.07	13.67	5.41	17.51	1.57	12.43	6.64
	Western region	4295	19.73	14.31	5.42	18.44	1.29	12.95	6.78
Divided by different administrative levels	Capital city	6673	30.65	21.52	9.14	24.62	6.03	19.56	11.09
	Non-capital city	15,097	69.35	55.37	13.98	60.14	9.21	43.58	25.76
	Total	21,770	100	76.89	23.12	84.76	15.24	63.14	36.85

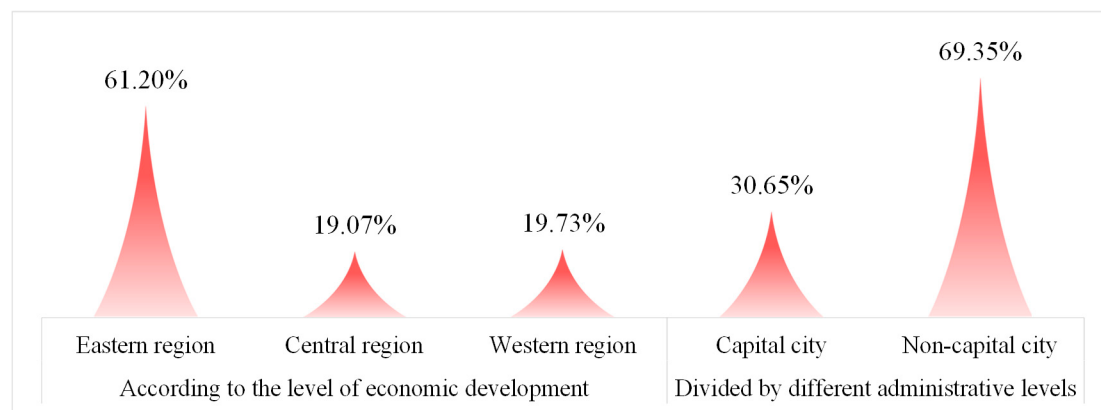


Figure 3. Proportion chart of different divided regions or city types.

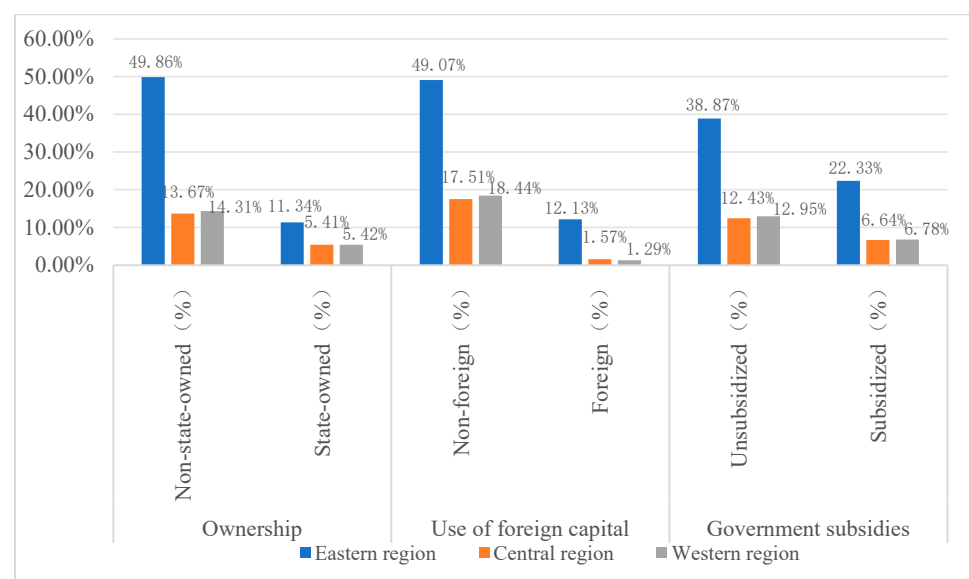


Figure 4. Proportion chart based on the level of economic development.

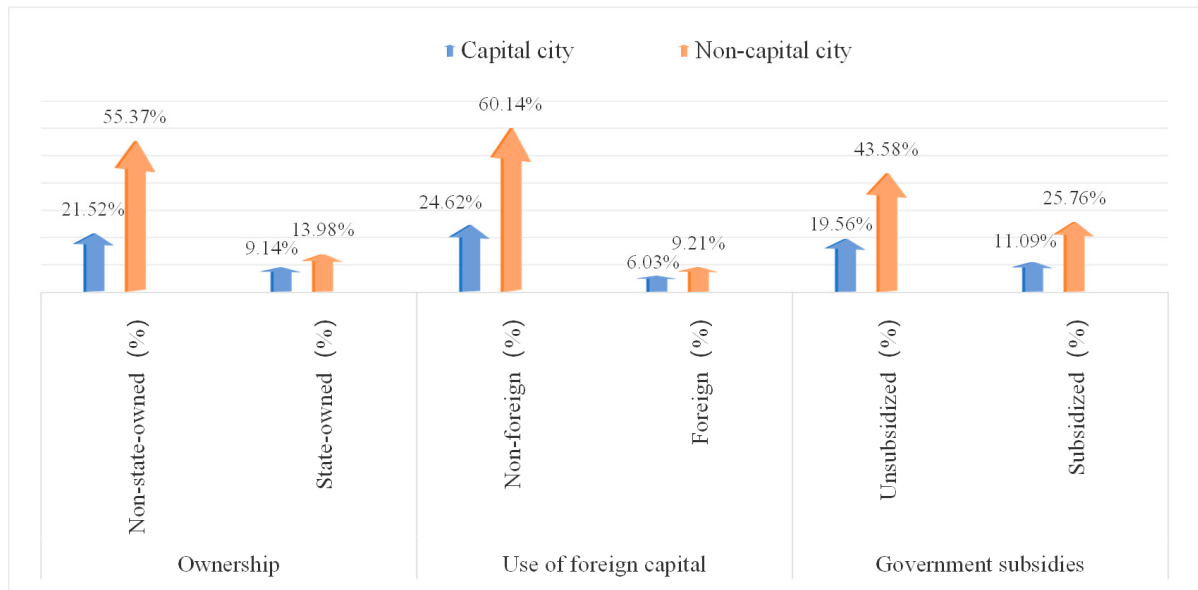


Figure 5. Proportion chart divided by different administrative levels.

4. Empirical Test and Results

4.1. Theoretical Model Testing

In Table 3, Model 1 is an OLS estimation, while Model 2 is an MLE estimation with $\ln \sigma_u = \ln \sigma_w = 0$ as added constraints. Models 3–7 are maximum likelihood estimates of two-tier stochastic frontier models under unconstrained conditions. Model 3 is the regression result of all variables, and Models 4–7 are the regression results after excluding insignificant variables or mis-convergence. Model 5 controls the time factors, Model 6 controls both regional economic development level and time factors, and Model 7 controls different regional administrative levels and time factors. From the estimation results, it is evident that the regression coefficient estimation results under the OLS method are basically consistent with those of the SFA2tier with or without constraints, indicating that the model selected is robust. At the same time, the OLS estimation is biased according to $E(\xi) = \sigma_w - \sigma_u + \sigma_v \neq 0$, and setting σ_w and σ_u to 0 is also unreasonable. However, Models 3–7 consider the bilateral impact of information factors on R&D costs, making the estimation more accurate. Finally, Model 7, with the best-fitting effect, is selected for R&D investment analysis and variance decomposition by comprehensively considering the test results of the logarithmic likelihood value and likelihood ratio.

Table 3. Regression estimation results of R&D investment mechanism model.

Dependent Variable	Inrand						
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
lnage	0.20 *** (12.13)	0.21 *** (12.48)	0.31 *** (18.12)	0.31 *** (17.23)	0.28 *** (16.67)	0.30 *** (17.61)	0.27 *** (15.71)
pollution	−0.44 *** (−24.41)	−0.45 *** (−24.72)	−0.48 *** (−25.75)	−0.47 *** (−24.31)	−0.47 *** (−25.43)	−0.48 *** (−25.71)	−0.43 *** (−23.49)
will	0.36 *** (11.57)	0.37 *** (11.71)	0.54 *** (16.60)	0.53 *** (15.62)	0.53 *** (16.49)	0.53 *** (16.46)	0.53 *** (16.42)
subordination	0.02 (0.51)	0.01 (0.34)	0.02 (0.58)				

Table 3. Cont.

Dependent Variable	Inrand						
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
subsidy	0.42 *** (14.30)	0.43 *** (14.53)	0.56 *** (18.38)	0.55 *** (17.38)	0.54 *** (17.96)	0.56 *** (18.36)	0.55 *** (18.33)
type	0.10 ** (2.53)	0.09 ** (2.37)	0.11 *** (3.12)	−0.04 * (−1.78)	0.14 *** (3.59)	−0.01 (−0.18)	0.10 ** (2.47)
size	0.29 *** (14.31)	0.30 *** (13.27)	0.22 *** (9.65)	0.17 *** (7.34)	0.23 *** (9.34)	0.18 *** (8.37)	0.24 *** (9.85)
foreign	0.39 *** (9.47)	0.41 *** (9.82)	0.60 *** (15.98)	0.66 *** (15.02)	0.70 *** (16.75)	0.64 *** (14.76)	0.68 *** (15.59)
tax	0.33 *** (15.23)	0.34 *** (12.39)	0.33 *** (11.45)				
_cons	5.44 *** (85.54)	5.45 *** (85.00)	6.48 *** (82.18)	6.47 *** (83.59)	6.71 *** (85.48)	6.31 *** (57.88)	6.06 *** (77.13)
year dummies	—	—	—	—	Control	Control	Control
area dummies	—	—	—	—	Control	Control	Control
adj. R ²	0.25	—	—	—	—	—	—
log-likelihood	−46,612.78	−47,488.52	−47,482.50	−47,390.06	−47,456.90	−47,305.89	
LR (chi ²)	3067.05	3153.47	5100.01	5359.96	5186.05	5590.77	
p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000
N	21,770	21,770	21,770	21,770	21,770	21,770	21,770

Note: *, **, and *** represent significant values at the 10%, 5%, and 1% levels, respectively, and the numbers in parentheses represent *t*-statistics.

4.2. Analysis of the Degree of Influence of Governments and Enterprises on Obtaining Residual R&D Investment

4.2.1. Interpretability of Bilateral Stochastic Frontier Model

From the variance decomposition of the SFA2tier estimation in Table 4, it is evident that unobservable factors such as the influence of governments and market enterprises play a crucial role in the formulation of R&D investment. Among them, the influence of market enterprises is more advantageous compared to the government's influence. $E(w - u) = \sigma_w - \sigma_u = -0.90$. The comprehensive effect of their influence is negative, which will form an R&D investment lower than the benchmark. At the same time, the total variance ($\sigma_v^2 + \sigma_u^2 + \sigma_w^2$) of *lnrand* is 4.54, in which their influence contributes 21%. In terms of the impact of the influencing factors on the formation of R&D investment, market enterprises have a stronger impact compared to the government, with a difference of 98%. Although the government has certain environmental policy constraints and the ability to regulate market enterprises, the majority of R&D investment decisions are made by market-driven businesses. The independence of scientific and technological innovation often makes it simpler for market enterprises to obtain a competitive advantage in the R&D investment decision-making process.

Table 4. Proportion of influence on R&D investment.

	Variable Meaning	Symbol	Measurement Coefficient
Mechanism of action	Stochastic error term	σ_v	1.89
	Influence of market enterprise	σ_u	0.98
	Government influence	σ_w	0.08

Table 4. Cont.

	Variable Meaning	Symbol	Measurement Coefficient
Variance decomposition	Total variance of stochastic terms	$(\sigma_v^2 + \sigma_u^2 + \sigma_w^2)$	4.54
	Proportion of influencing factors in total variance	$(\sigma_u^2 + \sigma_w^2) / (\sigma_v^2 + \sigma_u^2 + \sigma_w^2)$	0.21
	Proportion of market enterprise influence	$\sigma_u^2 / (\sigma_u^2 + \sigma_w^2)$	0.99
	Proportion of government influence	$\sigma_w^2 / (\sigma_u^2 + \sigma_w^2)$	0.01

4.2.2. The Extent to Which Both the Government and the Firm Capture the Residual Influence of R&D Investment

In order to further analyze the surplus and net surplus of R&D investment acquired by both governments and market enterprises during the formation process of R&D investment, the unilateral effects have also been estimated. From Table 5, it can be seen that the surplus captured by government influence will overestimate the benchmark by 5.50%, while the surplus captured by market enterprise influence will underestimate the benchmark by 49.91%. The difference in influence between the governments and market enterprises has resulted in actual R&D investment being 44.41% lower than the benchmark. In other words, the influence of market enterprises has squeezed out some of the government's remaining R&D investment.

Table 5. Total surplus of both the governments and market enterprises.

Average (%)	Standard Deviation (%)	Q1 (%)	Q2 (%)	Q3 (%)	Average (%)
Government: $E(1 - e^{-w} / \varepsilon)$	5.50	0.14	5.39	5.49	5.59
Market enterprise: $E(1 - e^{-u} / \varepsilon)$	49.91	11.94	41.17	47.69	56.38
Net surplus: $E(e^{-u} - e^{-w} / \varepsilon)$	−44.41	11.43	−50.64	−42.07	−35.51

Note: Q1, Q2, and Q3 represent the 25th, 50th, and 75th percentiles, respectively.

The quartile results in Table 5 can more directly reflect the distribution characteristics of enterprise surplus and government surplus, indicating that market enterprises occupy an absolutely dominant position in technological innovation. Specifically, it can be seen from the results of the first quartile, second quartile, and third quartile that the vast majority of market enterprises capture more surplus than the government during the formation of R&D investment, resulting in actual R&D investment being lower than the benchmark. The government's guiding and overseeing role in compelling market enterprises to engage in sustainable production is a possible explanation for transformation, upgrading, and technological innovation through strong environmental policies. Achieving this production effect requires independent innovation within the enterprise, yet enterprises often take other actions to avoid R&D investment.

Therefore, research Hypotheses 1a and 1b are supported.

From Figure 6, it can be seen that the surplus frequency distribution of market enterprises exhibits a clear right-trailing feature, and the surplus captured exceeds 80% in places where market enterprises have greater domination. At this point, market enterprises have absolute discourse power. The frequency distribution of net surplus shows a clear left-trailing characteristic, and all are negative, indicating that the government has accepted an R&D investment lower than the benchmark during the formation process. Market enter-

prises have an absolute influence, and the government’s “visible hand” is malfunctioning, reflecting the difficulty of implementing strong environmental policies during this stage.

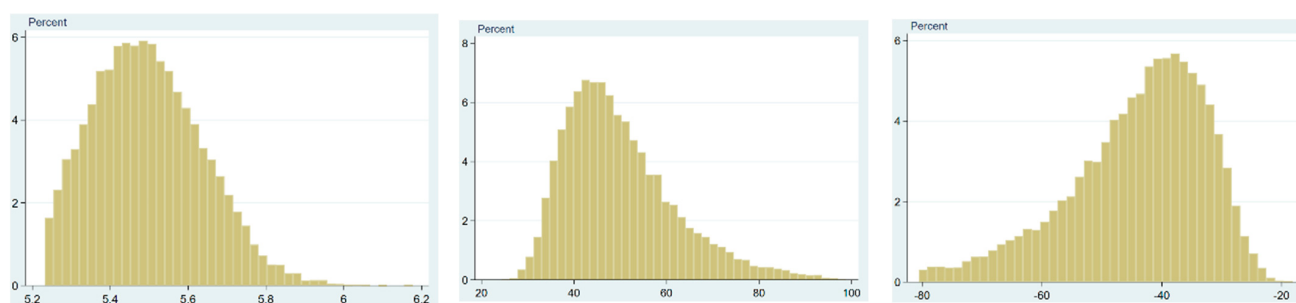


Figure 6. Frequency distribution of surplus acquired by governments, market enterprises, and net surplus.

4.3. Heterogeneity Analysis of Residual R&D Input Obtained by the Government and Enterprises

4.3.1. Heterogeneity Analysis at Different Stages of Economic Development

Environmental protection efforts have steadily increased over the past decade, and residents’ awareness of environmental protection has progressively grown [52]. Thus, does the influence of governments and market enterprises change with the implementation of strong environmental policies? From Table 6, it can be seen that the net surplus of governments and market enterprises gradually expanded during the period from 2005 to 2006, but gradually decreased during the period from 2006 to 2010. Since 2006, local energy conservation and emission reduction have played a significant role in the promotion performance evaluations of government officials. This has prompted the government to increase the impact of capturing surplus in the formation of R&D investment, indicating that strong environmental policies can effectively correct the distorted behavior of insufficient R&D investment by market enterprises.

Table 6. Net surplus of R&D investment acquired by both governments and market enterprises at different stages of economic development.

Year	Average (%)	Standard Deviation (%)	Q1 (%)	Q2 (%)	Q3 (%)
2005	−44.00	11.28	−50.52	−42.03	−35.60
2006	−44.11	11.63	−51.06	−42.23	−35.40
2007	−43.96	11.37	−50.44	−41.93	−35.55
2010	−41.35	10.23	−49.15	−40.56	−34.29

Note: Q1, Q2, and Q3 represent the 25th, 50th, and 75th percentiles, respectively.

4.3.2. Heterogeneity Analysis of Different Administrative Areas

In addition to examining the temporal distribution characteristics of government and market enterprise net surpluses, the regional distribution characteristics of net surpluses have also been analyzed. From Table 7, it can be seen that the net surplus in the east–west direction decreased from −43.53 to −45.04, and the net surplus in non-provincial capital cities was 0.08 percentage points higher than that in provincial capital cities. Specifically, the influence of market enterprises is 43.53% stronger than that of governments in the eastern region, the influence of market enterprises in the central region is 44.62% stronger than that of the governments, the influence of market enterprises in the western region is 45.04% stronger than that of the governments, the influence of market enterprises in provincial capital cities is 44.08% stronger than that of the governments, and the influence of market enterprises in non-provincial capital cities is 44.00% stronger than that of the governments. This indicates that the influence of governments and market enterprises in the formation of R&D investment varies depending on regional economic development and

administrative levels. On the one hand, the relatively less advanced central and western regions have more relaxed pollution control, making it easier for polluting enterprises to obtain policy exemptions and reduce R&D investment [53], which has resulted in a relatively strong impact. On the other hand, provincial capital cities may also have stronger environmental preferences due to excessive attention from superiors and smoother political expression from residents, and officials will relocate unrelated polluting enterprises at all costs [54]. The remaining enterprises often have strong political connections [47], and they have enough power to enhance their level of influence. Consequently, the influence of government departments and businesses on China's R&D investment varies across economic developmental stages and administrative districts.

Table 7. Net surplus of R&D investment acquired by the governments and market enterprises in different administrative districts.

	Region	Average (%)	Standard Deviation (%)	Q1 (%)	Q2 (%)	Q3 (%)
Divided by economic development	East	−43.53	11.39	−50.06	−41.58	−35.06
	Central	−44.62	11.24	−50.87	−42.99	−36.29
	West	−45.04	11.69	−52.10	−42.88	−36.23
Divided by different administrative levels	Provincial capital	−44.08	11.77	−51.05	−41.73	−35.19
	Non-provincial capital	−44.00	11.28	−50.44	−42.20	−35.64

Note: Q1, Q2, and Q3 represent the 25th, 50th, and 75th percentiles, respectively.

Therefore, Hypothesis 2 is supported.

4.4. The Decisive Factor Test of the Residual Impact Degree of R&D Investment for Both Governments and Enterprises

According to Table 3, factors such as subsidies, ownership, enterprise scale, enterprise age, and foreign investment have a substantial effect on the formation of R&D investment. Based on this, the determinants of the influence of both the governments and market enterprises are further analyzed from these perspectives.

4.4.1. The Influence of the Government and Enterprises on the Remaining R&D Input Under the Subsidy Factor

There is significant controversy over the impact of direct subsidies on R&D investment by governments and market enterprises. When the level of industry–university research cooperation between enterprises is low, market enterprises have a significant impact, and government subsidies are required to encourage enterprises to increase R&D investment [55]. However, subsidies may even completely replace enterprise R&D investment. The existence of the “rent-seeking” problem has led to a reversal in the influence of governments and market enterprises in R&D investment.

According to Table 8, it can be seen that governments have acquired less R&D investment surplus under both subsidized and unsubsidized conditions, while market enterprises have acquired more R&D investment surplus under subsidized conditions than under unsubsidized conditions, resulting in a smaller net surplus for governments and market enterprises under subsidized conditions. Government subsidies have reduced the share of investment that companies originally used for R&D. Enterprises may use subsidies elsewhere, leading to moral violations and adverse selection risks. This enables enterprises to respond more flexibly to technological R&D, thereby having a greater impact.

Table 8. Surplus R&D investment acquired by both governments and enterprises under subsidies.

Variable	Average (%)	Standard Deviation (%)	Q1 (%)	Q2 (%)	Q3 (%)
With subsidies (subsidy = 1)					
Government: $E(1 - e^{-w}/\epsilon)$	5.50	0.14	5.39	5.49	5.59
Enterprise: $E(1 - e^{-u}/\epsilon)$	49.99	12.21	41.05	47.48	56.34
Net surplus: $E(e^{-u} - e^{-w}/\epsilon)$	−44.49	11.60	−50.50	−41.83	−35.39
Without subsidies (subsidy = 0)					
Government: $E(1 - e^{-w}/\epsilon)$	5.50	0.14	5.39	5.48	5.59
Enterprise: $E(1 - e^{-u}/\epsilon)$	49.87	11.78	41.22	47.82	56.42
Net surplus: $E(e^{-u} - e^{-w}/\epsilon)$	−44.37	11.33	−50.73	−42.22	−35.59

Note: Q1, Q2, and Q3 represent the 25th, 50th, and 75th percentiles, respectively.

Therefore, hypothesis 3a is supported.

4.4.2. The Residual Influence of Ownership Nature, Scale, Age, and Other Factors on Both Governments and Enterprises to Obtain R&D Investment

(1) The degree of influence of the nature of enterprise factors of ownership

Compared to state-owned enterprises, non-state-owned enterprise shareholders effectively oversee management's decision-making behaviors and reduce management's agency problem in their own best interests. At the same time, due to the high degree of unity of control and cash flow, non-state-owned capital has a stronger motivation and ability to participate in the company's technological R&D investment [56,57].

Table 9 demonstrates that the influence of governments and market enterprises under various ownership structures differs significantly. The influence of non-state-owned enterprises is greater than that of state-owned enterprises, whereas the government's influence in the formulation process of R&D investment is the same for both types of enterprises. This causes non-state-owned enterprises and the government to have a smaller net surplus than state-owned enterprises and the government. Compared to state-owned enterprises, non-state-owned enterprises have fewer ties to the government, greater operating system flexibility, and greater autonomy. They also have greater R&D manipulation power, giving them an advantage in the R&D investment formulation process.

Table 9. Surplus R&D investment acquired by both governments and enterprises under their ownership.

Variable	Average (%)	Standard Deviation (%)	Q1 (%)	Q2 (%)	Q3 (%)
Non-state-owned (type = 0)					
Government: $E(1 - e^{-w}/\epsilon)$	5.50	0.14	5.39	5.48	5.59
Enterprise: $E(1 - e^{-u}/\epsilon)$	49.54	11.80	41.21	47.82	56.38
Net surplus: $E(e^{-u} - e^{-w}/\epsilon)$	−44.04	11.37	−50.69	−42.23	−35.57
State-owned (type = 1)					
Government: $E(1 - e^{-w}/\epsilon)$	5.50	0.14	5.39	5.49	5.59
Enterprise: $E(1 - e^{-u}/\epsilon)$	49.48	12.40	41.05	47.23	56.44
Net surplus: $E(e^{-u} - e^{-w}/\epsilon)$	−43.98	11.62	−50.40	−41.58	−35.38

Note: Q1, Q2, and Q3 represent the 25th, 50th, and 75th percentiles, respectively.

(2) The influence degree under the enterprise size factor

Enterprise size may have an impact on governments and market enterprises in R&D investment through various channels. Large-scale enterprises are usually more likely to form market forces, making them more influential in determining R&D investment, which will lead to blind confidence and falling into the “competency trap”.

From Table 10, it can be seen that the influence of large-scale enterprises is 0.82% stronger than that of small-scale enterprises, while the degree of government influence remains basically unchanged under both large-scale and small-scale conditions. On the one hand, small businesses confront greater pressure to survive in the competitive environment, and their desire to succeed through innovation is stronger and more innovative. On the other hand, large-scale enterprises often pay more taxes, accommodate more employment, and have a strong ability to transfer pollution. Government financial funds are highly dependent on them, and they are happy to see enterprises use their limited funds for profitable activities rather than R&D investments, making it easier for them to gain an advantageous position in the negotiation process of R&D investment.

Table 10. Surplus R&D investments acquired by both governments and enterprises, related to enterprise size.

Variable	Average (%)	Standard Deviation (%)	Q1 (%)	Q2 (%)	Q3 (%)
Small-scale (size = 0)					
Government: $E(1 - e^{-w}/\epsilon)$	5.50	0.14	5.39	5.49	5.59
Enterprise: $E(1 - e^{-u}/\epsilon)$	49.53	11.76	41.19	47.73	56.41
Net surplus: $E(e^{-u} - e^{-w}/\epsilon)$	−44.03	11.34	−50.69	−42.13	−35.55
Large-scale (size = 1)					
Government: $E(1 - e^{-w}/\epsilon)$	5.50	0.15	5.40	5.50	5.60
Enterprise: $E(1 - e^{-u}/\epsilon)$	50.35	13.24	41.05	47.24	56.30
Net surplus: $E(e^{-u} - e^{-w}/\epsilon)$	−45.15	12.08	−50.05	−41.39	−35.26

Note: Q1, Q2, and Q3 represent the 25th, 50th, and 75th percentiles, respectively.

(3) The influence degree in relation to the enterprise age factor

The lifecycle is the dynamic trajectory of enterprise development and growth, and enterprises at different stages of the lifecycle face varying financial constraints, entry into and exit from the market, and dependence on production organizations. Therefore, there is heterogeneity in the R&D investment behavior faced by enterprises at different stages.

From Table 11, it can be seen that the net surplus of governments and market enterprises is −43.79% during the growth period of market enterprises, and the influence of enterprises is the smallest. On the one hand, enterprises in the start-up period can flexibly choose to enter and exit the market, thereby having a significant impact on R&D investment. On the other hand, there is a widespread problem of organizational inertia in enterprises, according to organizational theory. As the enterprise age is growing, their business philosophy, technology, and management methods gradually solidify, and their dependence on the original production model becomes stronger. Organizational inertia gradually becomes clearer, making it easier to gain advantages in the process of R&D investment formation.

Table 11. Surplus R&D investment acquired by both the governments and enterprises relative to enterprise age.

Variable	Average (%)	Standard Deviation (%)	Q1 (%)	Q2 (%)	Q3 (%)
Start-up (age ≤ 10)					
Government: $E(1 - e^{-w}/\epsilon)$	5.49	0.14	5.38	5.47	5.57
Enterprise: $E(1 - e^{-u}/\epsilon)$	50.26	11.69	42.09	48.65	57.28
Net surplus: $E(e^{-u} - e^{-w}/\epsilon)$	−44.77	11.31	−51.54	−43.06	−36.47
Growth ($10 < \text{age} \leq 30$)					
Government: $E(1 - e^{-w}/\epsilon)$	5.50	0.14	5.39	5.49	5.60
Enterprise: $E(1 - e^{-u}/\epsilon)$	49.29	11.81	40.94	47.51	56.07
Net surplus: $E(e^{-u} - e^{-w}/\epsilon)$	−43.79	11.41	−50.42	−41.92	−35.30
Maturity (age > 30)					
Government: $E(1 - e^{-w}/\epsilon)$	5.49	0.14	5.39	5.49	5.59
Enterprise: $E(1 - e^{-u}/\epsilon)$	49.78	12.38	41.45	47.66	56.71
Net surplus: $E(e^{-u} - e^{-w}/\epsilon)$	−44.29	11.54	−50.90	−41.97	−35.75

Note: Q1, Q2, and Q3 represent the 25th, 50th, and 75th percentiles, respectively.

Therefore, Hypothesis 3b is supported.

(4) Degree of influence of foreign capital

Foreign investment injection compensates for the insufficient R&D funds of enterprises themselves and enables them to directly obtain advanced experience and technology from foreign enterprises. However, an enterprise may also lose the motivation and ability for independent innovation due to long-term technological dependence, thereby affecting the influence of market enterprises in the R&D investment process [58].

From Table 12, it can be seen that governments have acquired a relatively small surplus of R&D investment with or without foreign investment, while enterprises have acquired a smaller surplus of R&D investment with foreign investment than without foreign investment, resulting in a larger net surplus for both governments and enterprises with foreign investment. Foreign-funded enterprises have an embedded technological competitive advantage and financial support from foreign parent companies. They are less affected by environmental policies [59] and are more willing to invest in R&D. However, non-foreign-funded enterprises assume a heavy tax burden, lack external financial support, and have difficulty with independent R&D. They often make every effort to choose a more deterministic end treatment method.

Table 12. Surplus R&D investment acquired by both governments and enterprises relative to foreign investment.

Variable	Average (%)	Standard Deviation (%)	Q1 (%)	Q2 (%)	Q3 (%)
With foreign investment (foreign = 1)					
Government: $E(1 - e^{-w}/\epsilon)$	5.50	0.14	5.39	5.49	5.60
Enterprise: $E(1 - e^{-u}/\epsilon)$	49.44	12.61	40.77	47.61	56.83
Net surplus: $E(e^{-u} - e^{-w}/\epsilon)$	−43.94	11.65	−50.77	−41.90	−35.11
Without foreign investment (foreign = 0)					

Table 12. Cont.

Variable	Average (%)	Standard Deviation (%)	Q1 (%)	Q2 (%)	Q3 (%)
Government: $E(1 - e^{-w}/\varepsilon)$	5.50	0.14	5.39	5.49	5.59
Enterprise: $E(1 - e^{-u}/\varepsilon)$	49.54	11.82	41.25	47.70	56.34
Net surplus: $E(e^{-u} - e^{-w}/\varepsilon)$	−44.04	11.39	−50.61	−42.09	−35.62

Note: Q1, Q2, and Q3 represent the 25th, 50th, and 75th percentiles, respectively.

Therefore, Hypothesis 3c is supported.

5. Discussion

This study aims to analyze the degree of influence and determining factors between governments and market enterprises across different stages of economic development and administrative regions, utilizing the bilateral stochastic frontier model (SFA2tier) based on information game theory. It employs micro-matching data from the China Industrial Enterprise Database and the China Industrial Enterprise Pollution Database to conduct an in-depth analysis of the R&D investment surplus and net surplus generated by both the government and market enterprises during the formation of R&D investments. This research estimates the unilateral effects of government and market enterprises, while also performing differential analysis based on two dimensions: varying stages of economic development and differing administrative regions.

The findings of this article reveal the following: (1) There exists a degree of influence between the government and market enterprises. In the formation process of R&D investments, although the government possesses the capability to constrain and regulate market enterprises through specific environmental policies, the initiation of R&D investments is predominantly dictated by market enterprises. The autonomy inherent in technological innovation often positions market enterprises advantageously during R&D investment decision-making. (2) The degree of influence varies between the government and market enterprises at different stages of economic development. The net surplus for both entities has gradually diminished from the pre-2008 development stage to the post-2008 development stage. (3) The influence between the government and market enterprises differs across administrative regions. Variations in regional economic development levels and administrative tiers lead to heterogeneity in the influence exerted during the formation of R&D investments. (4) The influence of both the government and market enterprises is affected by subsidy factors. Regardless of the presence of subsidies, the government acquires only a relatively modest amount of R&D investment surplus. However, market enterprises benefit more from R&D investment surplus with subsidies (49.99%) compared to without subsidies (49.87%), resulting in a diminished net surplus for both parties. (5) The influence of both entities is also determined by the ownership structure of enterprises. The degree of influence of non-state-owned enterprises surpasses that of state-owned enterprises, while the government's influence during the R&D investment formation process remains consistent across both types of enterprises. (6) The influence of both government and market enterprises is related to enterprise size. The impact of large-scale enterprises (50.35%) is 0.82% greater than that of small-scale enterprises (49.53%), while the degree of government influence remains largely unchanged for both large and small enterprises. (7) The influence of both the government and market enterprises is also linked to the age of the enterprises. During the growth stage, the net surplus between the government and market enterprises is −43.79%, indicating the lowest degree of influence on enterprises at 49.29%, which is lower than the startup stage (50.26%) and the mature stage (49.78%). (8) The influence of both the government and market enterprises is further affected by foreign investment factors. Regardless of the presence of foreign investment, the government

secures only a relatively small amount of R&D investment surplus (5.5%), while enterprises with foreign investment (49.44%) experience a lower R&D investment surplus compared to those without foreign investment (49.54%), resulting in a larger net surplus between the government and enterprises with foreign investment.

The primary contributions of this study are as follows: (1) Innovation in modeling and measurement of information asymmetry. This study introduces the bilateral stochastic frontier model (SFA2tier) to assess the degree of information asymmetry, representing a significant advancement in the field of research and development investment. This model more accurately captures the information asymmetry issues between the government and market enterprises in R&D investment decision-making, thereby providing a novel methodology for future research. (2) Development of a multidimensional analytical framework. The study constructs an analytical framework encompassing multiple dimensions, including economic development stage, administrative region, and enterprise characteristics. This framework facilitates a comprehensive understanding of the complexity and dynamics of information asymmetry, offering a broader perspective for research. (3) Systematic identification of decisive factors. By analyzing a substantial amount of micro-matching data, this study systematically identifies the critical factors influencing information asymmetry in R&D investment, such as government policies, enterprise ownership, enterprise size, enterprise age, and foreign investment participation. These findings provide a theoretical basis for policy formulation and enterprise decision-making. (4) New insights into the roles of government and market enterprises. The research reveals that while the government plays a vital role in environmental policies and related areas, market enterprises often hold a dominant position in R&D investment decisions. This finding challenges the traditional singular perspective on the government's role and offers a fresh viewpoint for examining the relationship between government and market entities.

6. Conclusions and Implications

6.1. Conclusions

Data from the China Industrial Enterprise Database and the China Industrial Enterprise Pollution Emissions Database have been matched, and the SFA2tier is employed to empirically analyze the impact and determinants of R&D investment in different administrative districts by governments and market enterprises at different economic development stages. The conclusions are as follows:

- (1) The influence of the government and market enterprises plays a significant role in accomplishing the ultimate R&D investment, with the influence of enterprises being greater than that of the government. Specifically, governments used their influence to increase R&D investment by 5.50%, while enterprises used their influence to reduce R&D investment by 49.91%. The combination of the two often resulted in actual R&D investment being 44.41% lower than the benchmark.
- (2) During the sample period, the influence gap between government and market R&D spending displays an inverted U-shaped pattern. It increased from 44.00% in 2005 to 44.11% in 2006 and then decreased to 41.35% in 2010. It can be observed that the influence of governments and businesses on the formulation of R&D investment differs at various phases of economic development, and that this influence difference also fluctuates due to differences in regional economic development and administrative levels.
- (3) The differences in subsidies, ownership, enterprise size, enterprise age, foreign investment, and other factors lead to a greater impact from market enterprises than the governments in the formation of R&D investment. The net surplus with foreign investment is 0.1% higher than that without foreign investment. In other words, subsidized,

non-state-owned, large-scale, and non-foreign-funded enterprises, as well as those in start-up and mature stages, can have a greater impact on the R&D investment process, freeing them from strong environmental policy constraints.

6.2. Implications

In response to the preceding conclusions, the following three aspects provide the corresponding countermeasures and recommendations:

- (1) Optimize the R&D investment mechanism. Local governments should actively guide enterprises to expand their R&D investment scale, disclose information on scientific and technological innovation in real time, and strengthen the driving effect of actual demand on enterprise R&D investment, thus forming an efficient R&D investment mechanism guided by the government and led by enterprises.
- (2) Design a multi-channel R&D investment system. In recent years, various environmental policies have been continuously introduced, effectively reducing the net surplus of the governments and market enterprises in R&D investment. At the same time, this net surplus also exhibits heterogeneity in different administrative districts. Therefore, a multi-channel R&D investment system should be designed in regions to avoid this net surplus being treated as a “package” by top-level design.
- (3) Implement differentiated policies. The primary reason for the disparity in influence between governments and market enterprises is the information factor of enterprises’ fundamental characteristics. The government should, on the one hand, distribute R&D subsidies in installments to prevent crowding out effects. On the other hand, the government should reinforce its oversight of the R&D investment behavior of non-state-owned enterprises, avoid enterprise restructuring to expand production scale, and increase the enthusiasm for R&D in new and established businesses.

6.3. Limitations and Future Research

The limitations of the study include the following three aspects:

Firstly, the single research method: This study adopts a relatively single research method to explore the relationship between government environmental policies, corporate pollution levels, and corporate R&D investment. As a result, it may overly rely on quantitative analysis methods and lack the assistance of qualitative analysis methods, making it difficult to deeply explore the decision-making logic of enterprises and the interaction mechanisms of different stakeholders in the policy implementation process. This makes it difficult for the research results to comprehensively present the complex factors that affect corporate R&D investment.

Secondly, limited data sources: Research data may only come from specific regions, time periods, or types of enterprises, resulting in sample limitations. This not only limits the universality of research results but may also lead to biased empirical results, which cannot accurately reflect the real differences in R&D investment decisions of enterprises in different regions and development stages when facing environmental policies and pollution issues. Additionally, comprehensive environment monitoring data is missing, which is available from environment agencies at different levels of government.

Thirdly, incomplete industry coverage: The research focuses on certain industries and fails to cover a wide range of industries. Different industries have unique technological characteristics, market structures, and environmental sensitivities, and their R&D investment has different response mechanisms to government environmental policies and corporate pollution levels. Only studying specific industries hampers the formation of general conclusions that are universally applicable to all industries.

Future research recommendations include the following three aspects:

Firstly, enriching research methods: Comprehensively utilize various research methods, such as case analysis and in-depth analysis of the entire process of typical enterprises making R&D investment decisions under the influence of environmental policies, combined with their pollution levels, to visually demonstrate the enterprise's response strategies. At the same time, conduct questionnaire surveys and interviews to obtain first-hand views of enterprise managers on the relationships among environmental policies, pollution control, and R&D investment, providing qualitative support for quantitative analysis and revealing the inherent connections between variables in a comprehensive manner.

Secondly, expanding data sources: Collect multi-period data from enterprises in different regions and development stages to increase sample diversity. Doing so allows for the integration of official statistical data, corporate annual report data, industry report data, and other multi-channel data to build a comprehensive dataset. In addition, with the help of big data technology, unstructured data sources such as social media and online public opinion can be obtained to enrich the data dimensions of the research and improve the accuracy and universality of the research results.

Thirdly, expanding the scope of industry research: Conduct in-depth research on different industries such as pharmaceuticals and agriculture. The pharmaceutical industry has a long research and development cycle, high investment, and is subject to strict environmental regulations; agriculture is greatly influenced by natural conditions, and its pollution emissions have a dispersed characteristic. Studying these industries will enable the comparison of similarities and differences in R&D investment decisions across industries under the influence of environmental policies and pollution levels, the extraction of universal laws, and further improvement of the theoretical system, as well as provide more targeted references for governments to formulate differentiated environmental policies and for enterprises to formulate R&D investment strategies.

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