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Green transition and climate adaptation: empirical evidence of corporate resilience in the low-carbon economy

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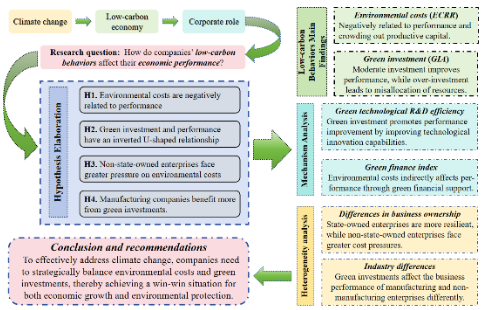
Graphical abstract



Abstract

As global climate change and management challenges grow, the low-carbon transition has become crucial for the sustainable development of enterprises. This study investigates the economic impact of corporate low-carbon behavior on operational performance using panel data from 2008 to 2022 for publicly listed Chinese companies. We find that the environmental cost-to-revenue ratio (ECRR) is negatively correlated with performance, indicating that higher environmental expenses short-term crowd out productive capital. In contrast, the green investment-to-assets ratio (GIA) exhibits an "inverted U-shaped" relationship with performance, with moderate investment enhancing performance through innovation, while excessive investment leads to resource misallocation and cost increases. Heterogeneity analysis shows that state-owned enterprises (SOEs) are more resilient to environmental costs, while non-state-owned enterprises (NSOEs) face greater cost pressures and performance risks. Additionally, green investment has a more significant positive impact on manufacturing firms due to their higher resource consumption and carbon intensity. This study also explores the transmission mechanisms through which green investment and environmental expenses affect performance via green technology R&D and green finance, respectively. These findings provide valuable insights for enterprises to balance environmental protection with economic benefits in their low-carbon transition.

Keywords: low-carbon behavior; green transformation; financial performance; empirical analysis; fixed-effects model; green investment and innovation

1. Introduction

With the rapid development of the global economy, the increasing emissions of greenhouse gases are contributing to global warming, resulting in natural disasters, the loss of biodiversity, and growing issues of resource scarcity and environmental pollution. The traditional high-energy consumption and high-pollution economic development model is becoming increasingly unsustainable (Calvin *et al*., 2023; Magnan *et al*. 2021; Meng *et al*. 2024). As a sustainable economic model, the low-carbon economy emphasizes reducing carbon emissions and improving resource utilization efficiency, aiming to achieve the harmonious coexistence of economic development and environmental protection. In this context, enterprises, as the main actors in economic activities, play a crucial role in not only their own survival and development but also in the broader societal pursuit of sustainable development (Martínez *et al*. 2022; Carradori *et al*. 2023). Corporate low-carbon behavior encompasses multiple aspects, including energy conservation and emission reduction, resource recycling, and green technological innovation. **Table 1** presents a comparative analysis of carbon reduction evaluation tools under ISO standards. Research indicates that corporate carbon emissions can influence investor preferences and have a significant impact on the overall value of enterprises (Choi *et al*., 2021; Adamolekun *et al*. 2022; Mbanyele, 2023; Prosperi and Zanin, 2024).

However, enterprises face numerous challenges in implementing low-carbon behaviors. The relationship between corporate environmental protection expenditures and business performance has become a widely discussed issue in both academia and industry, yet no consensus has been reached to date. Based on sustainable development theory, companies are required to take active measures to reduce their negative environmental impact while pursuing economic benefits (Horváthová, 2010). Such low-carbon behaviors help firms accumulate both tangible and intangible resources, thereby enhancing their competitive advantage (Shmelev and Gilardi, 2025).

Table 1. Comparison of features of various carbon emission reduction measurement tools

No.	Carbon Reduction Tool	Scope of Impact	Market-Based Approach	Certainty and Predictability of Cost Reduction	Management Cost	Impact on Income Distribution	Acceptability
1	Carbon Tax	Broad, entire economy	Price-based external cost internalization	High	Low	Complex, depends on tax revenue use	Low
2	Carbon Emission Trading Rights - Auction	Narrow, large enterprises	Quantity-based external cost internalization	Low	Medium	Complex, depends on auction revenue use	Low
3	Carbon Emission Trading Rights - Free Allocation	Narrow, large enterprises	Quantity-based external cost internalization	Low	Medium	Increases income distribution inequality	High
4	Combined Emission Trading Rights - Auction	Narrow, large enterprises	Combination of 1 and 2	Medium	Medium	Between 1 and 2	Low
5	Combined Emission Trading Rights - Free Allocation	Narrow, large enterprises	Combination of 1 and 3	Medium	Medium	Between 1 and 3	Medium
6	Subsidy - Reducing Investment in Emission Reduction	Narrow, some enterprises, residents	Internalization of external benefits	Medium	Uncertain	Uncertain	High
7	Subsidy - Subsidy for Renewable Energy	Broad, entire economy	Internalization of external benefits	Medium	Uncertain	Uncertain	High

On the other hand, neoclassical economic theory argues that corporate environmental protection expenditures crowd out productive capital, leading to declines in productivity and profits (Tsoulfidis, 2024; Yang *et al*., 2025; Liu *et al*., 2025; Luo *et al*., 2025). This perspective emphasizes that, in the context of limited resources, environmental protection expenditures may have a negative impact on corporate performance.

Porter's hypothesis challenges this traditional view, proposing that in a dynamic competitive environment, green investment under environmental regulations can be transformed into technological innovation, thereby creating competitive advantages and achieving a win-win situation in both environmental and business performance (Zhang *et al*., 2024).

This perspective has prompted some scholars to re-examine the question of whether the costs associated with green initiatives for enterprises are worthwhile. For instance, Sueyoshi and Wang's study found that green investments and other expenditures in the U.S. energy sector significantly improved business performance, as measured by return on assets, and environmental performance, as measured by carbon emissions (Liu *et al*. 2024). However, CSR theory further emphasizes that while enterprises pursue economic profits, they must also bear corresponding social responsibilities, including environmental protection, social welfare, and employee rights (Awa *et al*., 2024). In the context of a low-carbon economy, the environmental responsibility of enterprises becomes particularly crucial. By implementing low-carbon behaviors, companies not only fulfill their social responsibilities but also make investments in their long-term development.

In order to deeply analyze the relationship between corporate low-carbon behavior and business performance, as well as its complex transmission mechanisms, this study selects data from Chinese listed companies from 2008 to 2022 as the sample. The analysis is conducted from two perspectives: ECRR and GIA, to quantify the level of investment in corporate low-carbon behavior. The specific explanations of these two variables are shown in **Table 2** below.

This study introduces control variables such as firm age and industry characteristics to mitigate potential confounding factors. After data preprocessing, regression analysis was conducted using the fixed-effects model, following the F-test and Hausman test, to examine the impact of green investment and environmental expenditures on corporate performance. The core objective of this study is to systematically investigate the specific transmission pathways through which environmental expenditures, such as green investment, influence business performance, revealing the deeper internal mechanisms by which corporate environmental spending affects operational outcomes. Furthermore, this study explores the following questions: Whether there are significant differences in the impact of GIA and ECRR on corporate performance; whether the effect of environmental expenditure on performance shows heterogeneity across different ownership types; and whether the impact of green investment on business performance varies across different industries. Through these analyses, this study aims to provide a more comprehensive and in-depth understanding of the economic consequences of corporate low-carbon behaviors. The contributions of this paper are as follows:

- This study addresses the limitation of previous research that conflates green investment and environmental expenses in environmental funding. Prior studies used environmental performance indicators that only reflected post-facto outcomes without differentiating the impacts of various environmental expenditure strategies. In contrast, our research distinguishes green investment from environmental expenses and analyzes their distinct effects on corporate performance, offering a more accurate assessment of how different low-carbon expenditures influence business outcomes.
- Existing studies mainly empirically examine the correlation between corporate environmental expenditures or low-carbon measures and business performance. Building on this foundation, this study systematically examines the specific transmission pathways through which green investments and other low-carbon behaviors affect corporate performance from multiple perspectives, thereby revealing the deeper, underlying mechanisms by which corporate environmental spending influences operational outcomes.
- By comprehensively considering ownership types and industry differences, this study delves into the unique challenges and opportunities faced by different types of firms in the process of low-carbon transformation. This multi-dimensional heterogeneity analysis not only enriches existing theories but also provides new insights and empirical support for enterprises in formulating differentiated environmental strategies.

Table 2. Description of core explanatory variables

	Environmental cost to revenue ratio	**Green investment asset ratio**
Definition	The ratio of a company's expense-based environmental costs to its operating revenue over a certain period.	The ratio of a company's capital expenditures on green investments to its total assets over a certain period.
Quantification method	ECRR =environmental costs / operating revenue	GIA = green investment / total assets
Nature of expenditure	Routine operating expense, does not form fixed assets.	Capital expenditure, requires depreciation or amortization over a certain period.
Specific content	• Waste gas treatment costs. • Environmental compliance costs. • Environmental monitoring costs. • Carbon emission trading costs. • Other environmental costs.	• Emission-reduction technology investment. • Energy-saving equipment investment. • Energy management system investment • Green supply chain management investment • Green technology research and development investment.
Relationship with corporate low-carbon actions	Reflects the direct costs a company incurs to meet current environmental requirements, forming the basic investment in low-carbon actions.	Reflects the strategic investment in low-carbon transformation, focusing on long-term benefits and sustainable development.
Characteristics	Reflect the proportion of expense-based expenditures made by a company to meet environmental regulations and improve environmental performance in its daily operations, mainly reflecting the cost-effectiveness and compliance level of short-term environmental investments.	Measure the proportion of long-term capital expenditures on green technology research and development, energy-saving and emission-reducing equipment purchases, etc., reflecting the strategic investment and long-term sustainable development potential in low-carbon transformation.

2. Literature review and hypothesis formulation

2.1. Theoretical framework

In the current context of increasingly prominent contradictions between global economic development and resource-environmental issues, sustainable development theory provides the core theoretical foundation for corporate low-carbon behavior. This theory emphasizes that economic development must be coordinated with resource and environmental protection to ensure that the needs of the present generation are met without compromising the ability of future generations to meet their own needs (Yu *et al*., 2025). At the corporate level, this implies that businesses must not only pursue economic benefits but also actively implement measures to reduce their negative environmental impacts (Ren *et al*., 2022). Specifically, through low-carbon behaviors such as energy conservation, emission reduction, improved resource efficiency, and the adoption of clean production technologies, enterprises can effectively reduce environmental harm while promoting their long-term development (Li *et al*., 2021; Su *et al*., 2024). Such low-carbon behaviors help companies accumulate tangible resources, such as advanced production technologies and equipment, while also enhancing intangible assets like brand reputation and social image, thereby strengthening their competitive advantages (Tu *et al*., 2021).

Sustainable development theory provides a macro-level framework for corporate low-carbon behavior, while corporate social responsibility (CSR) theory further clarifies the specific responsibilities and investment value of businesses in environmental protection. CSR theory emphasizes that in the pursuit of economic interests, businesses must assume corresponding social responsibilities, including environmental protection, social welfare, and employee rights (Brin and Nehme, 2019). In the context of a low-carbon economy, the environmental responsibility of businesses becomes especially important. By implementing low-carbon behaviors such as energy conservation, emission reduction, and clean production, companies not only fulfill their social responsibilities but also invest in their long-term development (Wei *et al*., 2024). Specifically, through low-carbon behaviors, companies can reduce their negative environmental impacts, minimize resource consumption, and reduce pollution emissions, thus achieving a win-win situation in both economic and environmental outcomes (Zhange *et al*., 2025). These low-carbon behaviors not only help businesses accumulate social capital, such as a positive corporate image and social reputation, but also enhance their market competitiveness (Liu *et al*., 2025). For instance, consumers are increasingly inclined to choose environmentally friendly products, and investors are paying more attention to a company's environmental performance. Therefore, engaging in low-carbon behaviors enhances a company's competitiveness in the market, leading to positive effects on business performance (Farida and Setiawan, 2022). Moreover, low-carbon behaviors can improve a company's risk management capabilities, as environmental issues often bring legal and reputational risks. By actively addressing environmental concerns, businesses can effectively mitigate these risks, thereby safeguarding their long-term stability and development (Chen *et al*., 2025).

Guided by sustainable development theory and CSR theory, stakeholder theory emphasizes the impact of low-carbon behaviors on relationships between businesses and various stakeholders from an external perspective. It suggests that a company’s survival and development depend not only on the efforts of shareholders and management but also on the influence of other stakeholders, including employees, customers, suppliers, government, and the general public (Linghu *et al*., 2025). In the context of a low-carbon economy, stakeholders are increasingly concerned with a company’s environmental responsibilities and low-carbon behaviors. By implementing low-carbon actions, such as reducing carbon emissions and improving resource efficiency, companies can not only meet stakeholders' expectations for environmental protection but also enhance their social image and brand value (Pérez Estébanez and Sevillano Martín, 2025). For example, consumers are increasingly inclined to choose environmentally friendly products, and governments tend to collaborate with companies that demonstrate strong environmental performance. Therefore, low-carbon behaviors help strengthen relationships with various stakeholders, thereby positively influencing a company’s image (Lopes De Sousa Jabbour *et al*., 2020). Moreover, low-carbon behaviors can improve employee satisfaction and loyalty, as employees are often more willing to work for companies that are socially responsible and environmentally conscious (Jing *et al*., 2023). These positive impacts are not only reflected in short-term financial performance but also in the long-term competitiveness and sustainability of the company.

The theory of corporate symbiosis further explores, from an internal perspective, the impact of low-carbon behaviors on internal collaboration and organizational efficiency, emphasizing the interdependence between a company and its stakeholders. As an integral part of the social ecosystem, a company’s survival and development rely on harmonious symbiotic relationships with external stakeholders such as the government, communities, and the environment. In the context of a low-carbon economy, the symbiotic relationship between a company and the environment becomes particularly crucial. By implementing low-carbon actions, such as energy conservation and environmental protection, companies can not only reduce their negative environmental impact but also enhance their relationships with external stakeholders, including the government and communities (Xie *et al*., 2024; Wells *et al*., 2021). For instance, by reducing carbon emissions and pollution, companies can gain government policy support and tax incentives, while simultaneously improving their image and reputation within communities. This improvement in symbiotic relationships creates a more favorable external development environment, thereby positively influencing the company’s growth (Zheng *et al*., 2024). Furthermore, there are symbiotic relationships between different departments within a company. The implementation of low-carbon behaviors requires interdepartmental collaboration, which helps improve organizational efficiency and innovation, ultimately driving the overall progress of the company (Sampene *et al*., 2024).

However, the traditional view based on neoclassical economic theory argues that corporate funds are limited, and expenditures on environmental protection may crowd out productive capital, thereby reducing a company’s production efficiency and operational performance (Batool *et al*., 2025). For instance, Jaggi and Freedman’s study demonstrates that companies with strong environmental performance do not necessarily achieve better operational performance. On the contrary, companies with higher pollution levels, despite investing more in environmental protection, tend to experience relatively lower economic returns (Jaggi and Freedman, 1992). Wagner's empirical analysis further confirms that under end-of-pipe treatment strategies, there is a significant negative correlation between environmental expenditures and operational performance, as measured by sales profit margin and return on equity (ROE) (Wagner, 2005). Similarly, Sueyoshi and Goto's research points out that due to inconsistencies between environmental protection legislation and the U.S. power structure, environmental investment expenditures exhibit a negative correlation with operational performance, as measured by return on assets, in the short term (Sueyoshi and Goto, 2009).

With the introduction of the "Porter Hypothesis," traditional views were challenged (Porter and Linde, 1995). The Porter Hypothesis argues that traditional views are based on the assumptions of static environmental regulation and that companies have already minimized costs, overlooking the core role of innovation in dynamic competitiveness. In this context, companies' green investment expenditures under environmental regulation can be transformed into technological innovation, thus gaining a competitive advantage and achieving a win-win in both environmental and operational performance. This perspective has prompted some scholars to reconsider the question of whether the costs associated with going green are worthwhile for businesses. For example, Sueyoshi and Wang's research found that green investment expenditures in the U.S. energy sector can significantly improve operational performance, measured by return on assets, and environmental performance, measured by carbon emissions (Sueyoshi and Wang, 2014). Antonietti and Marzucchi (2014)'s study, using Italy's manufacturing industry as an example, confirmed that tangible green investments could improve production efficiency, leading to higher export performance (Antonietti and Marzucchi, 2014). Additionally, scholars have verified the positive correlation between green investment or environmental expenditure and operational performance based on empirical data from the French food industry and Spanish listed companies (Huiban, J.P.; Musolesi, 2012; Garcés-Ayerbe, 2017). Some researchers have also pointed out that the timing of environmental investments is crucial to a company's operational performance; firms that adopt proactive environmental strategies and make early environmental investments tend to achieve greater economic benefits (Nehrt, 1996).

The traditional views and the Porter Hypothesis are in opposition, while the perspective of complex mechanisms further deepens the understanding of this complexity. It reveals the intricate nature of the impact of low-carbon behavior on business performance, indicating that the relationship between a company's low-carbon behavior expenditures and its operational performance is not always linear or significant. Nakamura and Eri, using Japanese companies as a sample, found that the short-term impact of increased environmental investment expenditures on performance was not significant, while the long-term impact was more pronounced (Nakamura, 2011). Pekovic *et al*using French companies as a sample, discovered that when the scale of environmental investment crosses the turning point of an "inverted U-shaped" curve, further environmental investments would harm operational performance Pekovic *et al*., (2018).

2.2. Hypothesis elaboration

2.2.1. Analysis of the relationship between corporate ECRR and operating performance

a) Initial cost burden and delayed returns

Corporate environmental expenditures impose immediate financial burdens with limited short-term returns. Empirical studies indicate that compliance-driven investments—such as waste treatment infrastructure, carbon emission trading, and pollution control technologies—constitute fixed operational costs without direct value-added outcomes. For instance, mandatory air pollution mitigation facilities require significant capital expenditure (CAPEX) and ongoing operational expenses (OPEX), yet fail to enhance product competitiveness or profitability in the short run (Wang *et al*. 2021). Furthermore, volatile carbon pricing mechanisms exacerbate cost pressures, as fluctuating emission quotas directly erode profit margins (Ben Lahouel *et al*., 2021). This cost-benefit asymmetry creates a monotonic negative correlation between environmental expenditure ratios and business performance during initial phases, as immediate cost increments outweigh delayed economic gains.

b) Long-term competitive dynamics and uncertainties

While environmental investments may foster sustainable competitiveness, their economic materialization remains non-linear and context-dependent. First, reputational gains (e.g., brand equity from clean production) require prolonged market recognition to translate into revenue growth. Second, industry-specific factors—such as technological parity among competitors and shifting consumer preferences—may dilute differentiation advantages. For example, in sectors with homogenous environmental strategies, early adopters fail to capture monopolistic rents (Rubashkina *et al*., 2015). Additionally, policy volatility (e.g., abrupt regulatory changes or carbon market instability) introduces systemic risks, potentially negating long-term returns. Consequently, the performance trajectory of environmental investments diverges from a simplistic monotonic trend, exhibiting fluctuation contingent on exogenous variables.

c) Resource allocation constraints and trade-offs

Beyond temporal considerations, environmental commitments pose a structural challenge through resource allocation trade-offs and opportunity costs, compounding both short- and long-term impacts. Environmental commitments necessitate strategic resource reallocation, often at the expense of core business activities. Finite corporate resources diverted to compliance reduce funding available for R&D or market expansion, thereby constraining innovation capacity (Horváthová, 2010). Simultaneously, opportunity costs arise when firms prioritize environmental projects over high-return alternatives. For instance, capital allocated to carbon capture technologies might otherwise fuel AI-driven operational efficiency programs with immediate ROI. This dual burden—direct cost escalation and forgone growth opportunities—perpetuates performance erosion, even if long-term environmental competitiveness partially mitigates losses.

Based on the above analysis, the following hypothesis is proposed:

Hypothesis 1. There is a negative correlation between a company's environmental expenditure-to-revenue ratio and its business performance.

2.2.2. Analysis of the relationship between corporate GIA and business performance

a) Initial promotion effect of technological innovation and efficiency improvement

In the early stages of green investment, companies can effectively improve resource utilization efficiency (Liu *et al*., 2021), reduce production costs, and minimize the negative environmental impact by introducing environmental protection technologies, improving production processes, and implementing energy-saving and emission-reduction measures. For example, by adopting advanced air pollution control and clean production technologies, companies not only meet environmental compliance requirements but also reduce energy consumption and waste treatment costs, thereby enhancing overall operational efficiency (Rumanti *et al*., 2023). In addition, green investment helps companies establish a positive social image and brand reputation, attracting environmentally conscious consumers and investors, thus gaining an advantage in market competition (Zhang *et al*., 2024).

b) Decreasing marginal utility due to technology diffusion and intensified market competition

The initial benefits of green investment primarily stem from technological innovation and efficiency improvement, but as technologies become widespread and market competition intensifies, these benefits gradually diminish as competitors replicate and neutralize the effects (Maghyereh *et al*., 2025). For example, once an environmental technology becomes widely adopted, its market differentiation effect weakens. As more companies enter the green market, market competition intensifies, leading to impacts on the price and profit margins of green products. For instance, in certain industries, the market share of eco-friendly products is divided among numerous companies, causing a decline in individual companies' market share and profitability. Therefore, although green investment still brings certain benefits, its marginal returns are significantly reduced.

c) Cost surge and resource misallocation due to overinvestment

On the one hand, when green investment exceeds a certain threshold, its negative impact on business performance begins to emerge. Overinvesting in green projects may lead to a surge in costs. For example, after meeting basic environmental compliance requirements, further improvement in environmental performance requires more resources and capital investment. The additional emission reduction costs in the carbon trading market become increasingly higher, while the marginal returns and economic benefits from these investments gradually decrease. On the other hand, excessive green investment leads to a resource allocation imbalance, concentrating too much capital and effort on environmental protection while neglecting other crucial productive investments and research and development activities. When companies overinvest in environmental equipment, it may lead to cash flow problems, impacting new product development and market expansion. This imbalance in resource allocation not only weakens a company's core competitiveness but may also increase operational risks and financial pressure, causing problems such as technological failures and low market acceptance. Moreover, while green financial policies promote green investments, they may cause resource misallocation due to financial frictions, further exacerbating the imbalance in internal resource distribution.

Based on the above analysis, the second hypothesis is proposed:

Hypothesis 2. There is an inverted U-shaped relationship between a company's green investment and business performance, with an inflection point.

2.2.3. Analysis of the differences in the impact of environmental protection expenses on business performance under different ownership structures

a) Differences in resource acquisition capacity

Research by Zhang shows that SOEs have a significant advantage in terms of policy support and are able to secure more government subsidies. They also have inherent advantages in financing channels, making it easier to obtain low-cost loans from banks and other financial institutions (Zhang *et al*., 2021). For example, state-owned banks tend to favor providing loans to SOEs, often offering more favorable loan conditions. This financing advantage allows SOEs to be more flexible in allocating funds to meet environmental investment needs, without overly relying on internal cash flow or cutting other critical investments. In contrast, NSOEs, especially small and medium-sized enterprises (SMEs), often face difficulties in obtaining financing, especially at high costs. Allen *et al*. note that NSOEs often encounter higher barriers and stricter credit conditions when seeking bank loans. Without direct government support, NSOEs are more likely to face higher thresholds and stricter credit conditions when obtaining loans (Allen *et al*., 2005). As a result, when environmental protection expenses increase, NSOEs may need to cut other productive investments or R&D expenditures, and may even face the risk of a cash flow crisis. This difference in resource acquisition capacity leads to a more significant decline in the business performance of NSOEs when environmental protection costs rise.

b) Policy bias creates uneven playing fields

SOEs often bear greater social responsibility and policy tasks. When formulating environmental protection policies, governments tend to consider the actual circumstances of SOEs and offer certain policy support and financial subsidies (Ou *et al*., 2023). For example, the government may provide SOEs with special environmental funds, tax reductions, or support for technological research and development to help them better cope with environmental compliance pressures. In contrast, NSOEs typically have difficulty obtaining the same level of policy support. Due to the lack of direct government support, NSOEs are more reliant on their own resources and market mechanisms to address environmental compliance pressures. This difference in policy support makes it more difficult for NSOEs to alleviate cost pressures through external assistance, leading to a more significant negative impact on business performance when environmental expenses increase.

c) Ownership structure determines risk resilience

Research by Bao and Yu shows that SOEs also have an advantage in terms of risk-taking capacity, enabling them to better handle challenges when environmental expenses rise (Bao *et al*., 2023). First, SOEs generally have stronger capital strength and more stable financial conditions, which allows them to better disperse risks when facing short-term cost pressures. For example, SOEs can use internal funds or asset restructuring to ease the financial pressure caused by rising environmental costs. In contrast, NSOEs, particularly SMEs, often face higher financial and operational risks. Due to a lack of strong capital strength and stable financial conditions, NSOEs are more likely to struggle in mitigating risks internally when environmental expenses increase. This difference in risk-taking ability results in a more significant decline in business performance for NSOEs as environmental costs rise.

Based on the above analysis, the third hypothesis is proposed:

Hypothesis 3. Compared to SOEs, NSOEs experience a more significant decline in business performance as their environmental protection expenses increase.

2.2.4. Analysis of the differences in the impact of green investments on business performance under different industry attributes

a) Direct benefits and industry chain integration advantages in manufacturing

Manufacturing enterprises generally have higher resource consumption and carbon emission intensities, making green investments in the manufacturing sector capable of generating more direct and significant benefits. On one hand, manufacturing companies can directly reduce production costs and improve production efficiency through green investments, such as adopting clean production technologies, improving production processes, and enhancing energy utilization efficiency (Zhu *et al*., 2024). For example, by investing in research and development and applying advanced energy-saving and emission-reduction technologies, companies can significantly reduce energy consumption and waste emissions, thus lowering long-term operating costs. These direct benefits make green investments in the manufacturing sector quickly translate into improved business performance. On the other hand, manufacturing enterprises often possess a relatively complete industry chain, which allows green investments to create synergies throughout the entire industry chain (He *et al.*, 2025). For example, by introducing green concepts into supply chain management and encouraging upstream and downstream companies to jointly implement environmental protection measures, they can form a green supply chain, thereby enhancing the competitiveness of the entire industry chain. This advantage of industry chain integration means that green investments in manufacturing not only improve the company's own business performance but also contribute to the sustainable development of the entire industry.

b) Indirect benefits and market dependence in non-manufacturing

In contrast, the impact of green investments on business performance in non-manufacturing sectors (e.g., services, high-tech companies) is relatively indirect and more dependent on the market environment and consumer preferences. First, non-manufacturing enterprises typically have lower resource consumption and carbon emission intensities, making it difficult for green investments to generate significant direct benefits in the short term. For example, service industry enterprises can reduce certain operating costs through measures such as green office practices and energy-saving initiatives, but their impact on overall business performance is relatively limited (Zhao *et al*., 2025). Secondly, the effectiveness of green investments in non-manufacturing enterprises is more dependent on the market environment and consumer preferences. For instance, in markets with strong environmental awareness, consumers are more inclined to choose environmentally friendly services or products, which allows non-manufacturing companies' green investments to bring a certain competitive advantage. However, in markets with weaker environmental awareness, the benefits of green investments are less likely to materialize. Therefore, the impact of green investments on the business performance of non-manufacturing enterprises exhibits greater market dependence and relatively lower correlation.

Based on the above analysis, the fourth hypothesis is proposed:

Hypothesis 4. There are significant differences in the impact and trends of green investments on business performance between manufacturing and non-manufacturing enterprises.

3. Empirical research design

3.1. Sample and data sources

Listed companies in China, as an important part of the economic system, have relatively standardized and transparent financial and environmental data disclosures, providing high-quality data support for research. Moreover, during this period, China underwent rapid industrialization and increasingly stringent environmental regulations, making the environmental expenditure behaviors of listed companies more valuable for study. Therefore, this study uses Chinese listed companies from 2008 to 2022 as the research subjects, employing panel data. The total expenditure related to environmental protection disclosed in the management expense details of the annual reports, collected manually, is used as a proxy for green expenditure. Green investment is sourced from the investment expenditure related to environmental protection, pollution prevention, ecological governance, and green production disclosed in the construction project details of the annual reports. Other variables are obtained from the Guotai'an database and the China Emission Accounts and Datasets (CEADs), covering the companies' financial statement information.

To ensure the completeness and representativeness of the data, strict data screening was conducted. First, years of companies marked as ST (special treatment) during the sample period were excluded to avoid interference with the research results caused by financial distress or operational anomalies. Second, for samples with missing data, the study chose to exclude them directly, rather than using imputation, to ensure the accuracy and reliability of the analysis. During the data processing, the study applied a 1% Winsorization to the main continuous variables to reduce the influence of extreme values on the regression results. Finally, the sample includes 33,981 environmental expenditure data points and 32,366 green investment data points.

3.2. Model construction and variable definition

This study selects ROE as the dependent variable, which measures a company's ability to generate returns using its own capital. A higher ROE indicates stronger profitability and better performance. ROE is influenced by two factors: return on assets and the equity multiplier. A company can improve its ROE by increasing asset utilization efficiency, under appropriate conditions, by increasing leverage, although the latter may increase financial risk. Therefore, ROE considers the capital structure and is more reflective of company performance from a shareholder's perspective, making it a suitable dependent variable.

To better explore the relationship between low-carbon behavior and business performance, both environmental expenditure and green investment are modeled separately. The Pearson correlation coefficient between these two variables in the study sample is only 0.0143, with a p-value of 0.5287, indicating a small and insignificant correlation. As a result, there is no significant mutual influence, and they can be included separately in the model.

In model I, ECRR is chosen as the explanatory variable. Its calculation method is as follows:

$$ECRR = \frac{EPET}{TR} \times 100\% \tag{1}$$

$$EPET = Direct\,Expenses + Indirect\,Expenses \tag{2}$$

In this model, TR represents total operating revenue, and EPET refers to the total environmental expenditure, which is the total amount spent by the company on environmental protection during a specific period. Direct Expenses refer to costs directly used for environmental protection, such as materials and equipment, while Indirect Expenses include environmental management, monitoring, and other related costs.

Model II uses the ratio of GIA as the explanatory variable. Its calculation method is as follows:

$$GIA = \frac{GIT}{TA} \times 100\% \tag{3}$$

$$GIT = \sum \left(Investment\,In\,Green\,Projects \right) \tag{4}$$

In this model, TA represents the total value of all assets owned by the company, and GIT refers to the total amount of green investment, which is the total investment made by the company in green projects (such as energy-saving and emission-reduction technology investments, energy-efficient equipment investments, energy management systems investments, etc.) during a specific period.

Table 3. Variable description

Variable	Explanation	Attribute
stkcd	Stock code	Categorical variable
year	Year	Time variable
ROE	Return on Equity	Dependent variable
ECRR	Environmental cost to revenue ratio	Explanatory variable for Model I
ECRRSq	Square of environmental cost to revenue ratio	
GIA	Green investment asset ratio	Explanatory variable for Model II
GIASq	Square of green investment asset ratio	
Lev	Asset-liability ratio	Control variable
SOE	Property rights nature (SOEs = 1, NSOEs = 0)	
ATO	Total asset turnover rate / agency cost	
FirmAge	Years since establishment	
Mshare	Management shareholding ratio	
Herfindahl5	Herfindahl index of equity concentration	
Mfg	Manufacturing industry (Yes = 1, No = 0)	

In the regression model, quadratic terms are included to test the nonlinear relationship between low-carbon behaviors, represented by green investment and environmental expenditure, and business performance. This also takes into account the lag effect of green investment and environmental expenditure, as well as issues related to endogeneity during the same period (Pekovic *et al*., 2018). The explanatory variables ECRR and GIA are processed with a one-period lag.

Model I: The regression model between the environmental ECRR and ROE is as follows:

$$ROE_{i,t} = a_0 + a_1 ECRR_{i,t-1} + a_2 ECRR^2_{i,t-1} + \sum \beta_i CONTROL_{i,t} + \varepsilon_{i,t} \quad (5)$$

Model II: The regression model between the environmental GIA and ROE is as follows:

$$ROE_{i,t} = a_0 + a_1 GIA_{i,t-1} + a_2 GIA^2_{i,t-1} + \sum \beta_i CONTROL_{i,t} + \varepsilon_{i,t} \quad (6)$$

In this model, the following variables are included as control variables. Drawing on the methods used by (Zanin, 2025; Algarni *et al*., 2022; Hu and Zhao, 2024; Z. Jia-Wen and Miaoshuo, 2024; Xie *et al*., 2024) this study selects asset-liability ratio (Lev), ownership type (SOE), company age (FirmAge), etc. as control variables. The specific descriptions and attributes are shown in **Table 3**. The calculation method for company age is as follows:

$$FirmAge = ln\left(Year_{current} - Year_{establishment} + 1\right) \quad (7)$$

Management shareholding ratio is calculated as follows:

$$Mshare = \frac{S_{insiders}}{T_{shares}} \quad (8)$$

In Equation (9), $S_{insiders}$ and T_{shares} represent the number of shares held by the board of directors, supervisors, and senior executives, and the total number of shares of the company, respectively. The calculation method for Herfindahl index of equity concentration (Herfindahl5) — is as follows:

$$Herfindahl5 = \sum_{i=1}^{5} (SH_i)^2 \quad (9)$$

In Equation (10), SH_i represents the ownership percentage of the i-th largest shareholder.

4. Empirical results analysis

4.1. Descriptive Statistics

Tables 4 and 5 present the descriptive statistics for the variables used in the regression models for Model 1 and Model 2. ROE, as the core indicator of business performance, has a mean value of 0.0492, with a minimum of -0.217 and a maximum of 0.418. Most companies in the sample exhibit stable profitability; however, a portion of companies have poor performance and even face losses.

Regarding the low-carbon behavior of Chinese listed companies, ECRR has a mean of 0.0168, a standard deviation of 0.0122, a minimum close to zero, and a maximum of 0.0800. This reflects significant variation in the environmental investment levels of Chinese listed companies. Some companies invest more in environmental protection due to industry characteristics or regulatory requirements, while others show insufficient attention to environmental responsibilities and make relatively lower investments.

Table 4. Descriptive statistics of sample data of model I using ECRR as explanatory variable

Variables	Observation	Mean	Standard Deviation	Minimum	Maximum
ROE	33,981	0.0492	0.069	-0.197	0.418
ECRR	33,981	0.0168	0.0122	7.14e-06	0.0800
ECRRSq	33,981	0.000432	0.000724	5.10e-11	0.00640
SOE	33,981	0.354	0.478	0	1
Lev	33,981	0.432	0.205	0.0278	0.934
ATO	33,981	0.613	0.415	0.0475	3.014
FirmAge	33,981	2.932	0.330	1.099	3.664
Mshare	33,981	0.130	0.192	0	0.705
Herfindahl5	33,981	0.157	0.112	0.0118	0.588
Mfg	33,981	0.658	0.474	0	1

Table 5. Descriptive statistics of sample data of model II using GIA as explanatory variable

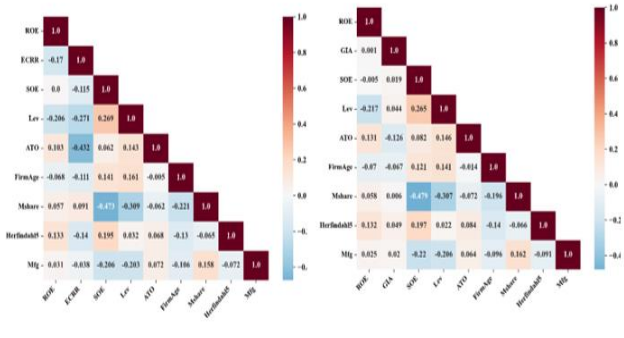
Variables	Observation	Mean	Standard Deviation	Minimum	Maximum
ROE	32,366	0.0496	0.169	-0.217	0.418
GIA	32,366	0.00848	0.0118	0	0.0996
GIASq	32,366	0.000211	0.000665	0	0.00992
SOE	32,366	0.366	0.482	0	1
Lev	32,366	0.434	0.202	0.0278	0.934
ATO	32,366	0.619	0.413	0.0475	3.014
FirmAge	32,366	2.919	0.334	1.099	3.664
Mshare	32,366	0.127	0.191	0	0.705
Herfindahl5	32,366	0.158	0.113	0.0118	0.588
Mfg	32,366	0.692	0.462	0	1

GIA has a mean of 0.00848, a standard deviation of 0.0118, a minimum of 0, and a maximum of 0.0996. This indicates that Chinese listed companies invest relatively little in green projects, and low-carbon expenditure is generally insufficient, revealing substantial potential for improvement in the low-carbon behavior of these companies.

4.2. Correlation analysis

Based on the Pearson correlation coefficients in **Tables 6 and 7**, in Model I, ROE shows a significant negative correlation with ECRR ($r = -0.170$, $p < 0.01$), which largely supports the expected hypothesis H1. Additionally, the debt-to-equity ratio (Lev) also exhibits a significant negative correlation with ECRR ($r = -0.271$, $p < 0.01$), indicating that companies with higher debt levels tend to invest less in environmental protection or have lower efficiency in environmental spending.

In Model II, the correlation between ROE and GIA is weak ($r = 0.001$) and not significant, suggesting that the relationship between green investment and corporate profitability may be more complex, requiring further empirical analysis to uncover its underlying mechanisms. Notably, GIA shows a significant positive correlation with the debt-to-equity ratio (Lev) ($r = 0.044$, $p < 0.01$), implying that highly leveraged companies are more likely to engage in green investments to improve their financial condition or market image.



(a) (b)

Figure 1. Heatmap of each variable in the model: (a) Model I: ECRR; (b) Model II: GIA

Table 6. Correlation test of model I with ECRR as explanatory variable

	ROE	ECRR	SOE	Lev	ATO	FirmAge	Mshare	Herfindahl5	Mfg
ROE	1								
ECRR	-0.170***	1							
SOE	0	-0.115***	1						
Lev	-0.206***	-0.271***	0.269 ***	1					
ATO	0.103 ***	-0.432***	0.062 ***	0.143 ***	1				
FirmAge	-0.068***	-0.111***	0.141 ***	0.16 1***	-0.005	1			
Mshare	0.057 ***	0.091 ***	-0.473***	-0.309***	-0.062***	-0.221 ***	1		
Herfindahl5	0.133 ***	-0.140***	0.195 ***	0.032 ***	0.068 ***	-0.130 ***	-0.065 ***	1	
Mfg	0.031 ***	-0.038***	-0.206***	-0.203***	0.072 ***	-0.106 ***	0.158 ***	-0.072 ***	1

*Note: ***, **, and * represent significance levels of 1%, 5%, and 10%, respectively. Similar notation is used in the following tables.*

Table 7. Correlation test of model II with GIA as explanatory variable

	ROE	GIA	SOE	Lev	ATO	FirmAge	Mshare	Herfindahl5	Mfg
ROE	1								
GIA	0.001	1							
SOE	-0.005	0.019 ***	1						
Lev	-0.217***	0.044 ***	0.265 ***	1					
ATO	0.131 ***	-0.126***	0.082 ***	0.146 ***	1				
FirmAge	-0.070 ***	-0.067 ***	0.121 ***	0.141 ***	-0.014 **	1			
Mshare	0.058 ***	0.006	-0.479***	-0.307***	-0.072***	-0.196***	1		
Herfindahl5	0.132 ***	0.049 ***	0.197 ***	0.022 ***	0.084 ***	-0.140 ***	-0.066***	1	
Mfg	0.025 ***	0.020 ***	-0.220 ***	-0.206 ***	0.064 ***	-0.096 ***	0.162 ***	-0.091 ***	1

Figure 1 shows the heat map of the two models, providing an intuitive perspective to understand the interrelationship between variables.

4.3. Multicollinearity test

The multicollinearity test results in **Table 8** show that the variance inflation factor (VIF) values of the variables in both Model 1 and Model 2 are well below the threshold of 10, which is commonly considered to indicate potential multicollinearity issues (Manning *et al*., 2008; Snee, 1983). Specifically, the average VIF value for Model I is 1.24, and for Model II, it is 1.17, indicating that there is no significant multicollinearity problem between the variables in both models. This ensures the robustness of the regression analysis results. These findings suggest that the model estimates are reliable and can be effectively used to analyze the relationship between corporate low-carbon behavior and operating performance.

4.4. Model selection

Table 9 presents the results of the F-test and Hausman test to verify the appropriateness of the chosen empirical regression method. First, the F-test was used to evaluate the suitability of the fixed effects model versus the pooled regression model. The results show that the p-values for both the overall model and the individual effects are statistically significant at 0, indicating that the fixed effects model better captures individual differences in the data. Therefore, the hypothesis of the pooled regression model is rejected. Subsequently, the Hausman test was conducted to further compare the random effects model and the fixed effects model. The results show that the prob > chi² value is significantly 0, leading to the rejection of the random effects model. Ultimately, the fixed effects model was selected for regression analysis.

Table 8. Results of multicollinearity test

Variable	ECRR		GIA	
	VIF	1/VIF	VIF	1/VIF
SOE	1.39	0.720085	1.40	0.722720
Lev	1.25	0.801631	1.19	0.844936
ATO	1.24	0.805071	1.07	0.938346
FirmAge	1.11	0.901184	1.09	0.920287
Mshare	1.39	0.721733	1.39	0.723355
Herfindahl5	1.04	0.960667	1.08	0.922126
Mfg	1.335	0.743304	1.03	0.969243
Mean VIF	1.24		1.17	

Table 9. Results of F test and Hausman test

Category	F test				Hausman test
	Model overall significance test	P value (overall model)	Individual effect significance test	P value (individual effect)	Prob>chi2
Model I	565.48	0.0000	2.59	0.0000	0.0000
Model II	422.72	0.0000	2.64	0.0000	0.0000

4.5. Regression analysis and robustness check

After the F-test and Hausman test, the fixed-effects model was selected for the panel data regression. The regression results for ECRR and GIA of Chinese listed companies on business performance are presented in columns (1) and (2) of **Table 10**, showing a noticeable difference between the two.

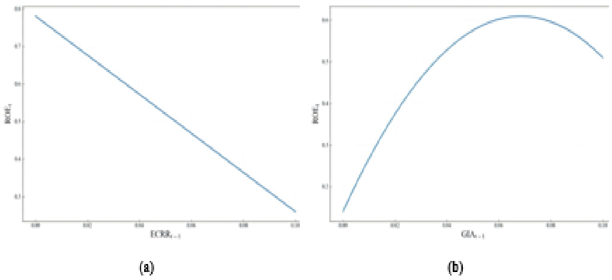


Figure 2. Regression relationship between corporate low-carbon behavior and business performance: (a) The relationship between ECRR and ROE; (b) The relationship between GIA and ROE

Column (1) shows a significant negative correlation between ECRR and ROE. The coefficient of the linear term for ECRR is -5.263, which is significant at the 1% level, while the quadratic term coefficient is 33.361, which is not significant. The characteristic graph of the relationship between business performance and ECRR is visualized in **figure 2(a)**. Therefore, ECRR is negatively correlated with ROE, indicating that as environmental protection expenditures increase, they crowd out productive capital and reduce production efficiency, leading to a significant decline in business performance (ROE), confirming Hypothesis 1.

Column (2) shows a different situation. The coefficient for GIA is 0.571, and the coefficient for GIASq is -4.156, both significant at the 1% level. This indicates that the relationship between green investment and business performance is non-linear, presenting a U-shaped shape with an inflection point. The characteristic graph of business performance with respect to green investment is visualized in **figure 2(b)**. When the level of green investment is low, increasing it will improve business performance. However, when green investment exceeds 0.073, further increases will actually reduce business performance. The current average value of green investment for Chinese listed companies is 0.00848, far below the inflection point, suggesting there is still significant room for improvement. This aligns with the findings of (Pekovic *et al*., 2018), whose study on French companies concluded a similar "inverted U-shaped" relationship between green investment and business performance. Thus, Hypothesis 2 is confirmed. To eliminate the possibility of spurious results and strengthen the persuasiveness of the regression outcomes, this study performs robustness checks by transforming data and substituting variables.

Table 10. Full sample regression and robustness test results

VARIABLES	Baseline model		Robustness check			
	Model I	Model II	Model I		Model II	
	ROE	ROE	lnROE	ROA	lnROE	ROA
	(1)	(2)	(3)	(4)	(5)	(6)
ECRR	-5.263***		-4.539***	-1.752***		
	(-21.49)		(-20.37)	(-20.88)		
ECRRSq	33.361		26.096	6.287		
	(1.33)		(1.60)	(1.25)		
GIA		0.571***			0.815***	0.440***
		(3.27)			(4.92)	(7.08)
GIASq		-4.156***			-8.996***	-5.153***
		(-3.39)			(-3.07)	(-4.68)
SOE	0.013***	0.012***	0.012***	0.004***	0.010***	0.003***
	(4.86)	(3.87)	(5.87)	(4.89)	(4.60)	(3.85)
Lev	-0.271***	-0.259***	-0.234***	-0.139***	-0.208***	-0.129***
	(-49.34)	(-44.17)	(-49.43)	(-78.03)	(-43.17)	(-71.01)
ATO	0.015***	0.079***	0.012***	0.008***	0.066***	0.031***
	(5.14)	(27.88)	(5.14)	(9.15)	(29.50)	(36.66)
FirmAge	-0.041***	-0.020***	-0.022***	-0.008***	-0.009***	-0.002**
	(-12.80)	(-6.09)	(-7.96)	(-7.72)	(-3.27)	(-2.17)
Mshare	0.015**	0.019***	0.010**	0.015***	0.012**	0.014***
	(2.32)	(2.82)	(1.97)	(7.37)	(2.21)	(6.79)
Herfindahl5	0.150***	0.182***	0.141***	0.068***	0.168***	0.079***
	(15.37)	(17.17)	(17.49)	(22.33)	(20.31)	(25.43)
Mfg	-0.009***	-0.010***	-0.009***	-0.002***	-0.010***	-0.002***
	(-3.83)	(-3.54)	(-4.66)	(-2.59)	(-4.75)	(-2.73)
Constant	0.327***	0.138***	0.250***	0.127***	0.096***	0.061***
	(27.44)	(12.36)	(24.85)	(33.45)	(10.47)	(17.89)
Observations	33,981	32,366	33,981	33,981	32,366	32,366
R-squared	0.085	0.157	0.115	0.218	0.092	0.190

*Note: The standard errors in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.*

Columns (3) and (5) in **Table 11** present the results of a robustness test after taking the logarithm of ROE. Columns (4) and (6) use ROA as a substitute for ROE in the robustness check. The results show that all variables demonstrate the expected significance and consistent direction across different models, indicating that the conclusions of this study are robust and not influenced by the choice of performance metrics.

5. Impact pathway testing and heterogeneity analysis

5.1. Impact pathway testing

In the Section 2.2, it was emphasized that the key to the impact of corporate low-carbon behavior on business performance lies in whether these behaviors can drive the long-term development of the enterprise through technological innovation, without significantly crowding out productive capital. Moreover, both corporate environmental activities and production operations rely on financial support, and financing constraints directly limit the optimization of business performance. Therefore, this section empirically tests the mechanisms through which green investment and environmental expenses affect business performance, from the perspectives of green technological R&D and green finance.

5.1.1. Green technological R&D efficiency

According to the endogenous growth theory, technological innovation is the core driving force of economic growth. As the primary participants in economic activities, enterprises' level of technological innovation directly affects their production efficiency and ability to transform their business models, thereby influencing corporate performance. This theory posits that technological innovation can directly enhance a firm's production efficiency by optimizing production processes and reducing production costs. Moreover, it can also strengthen a firm's market competitiveness and risk resistance by developing new products and services and expanding into new markets. From an economic perspective, technological innovation has a profound impact on a firm's long-term performance. It not only translates directly into economic benefits but also indirectly enhances a firm's market position and long-term returns by boosting its market competitiveness and brand value. This assertion is supported by a substantial body of empirical evidence. For example, Liu *et al*. (2024) found that green technological innovation significantly improves corporate financial performance, with a more pronounced effect in manufacturing firms (Liu *et al*., 2024). Similarly, Antonietti and Marzucchi (2014) confirmed the positive impact of technological innovation on corporate export performance through their research on Italian manufacturing companies (Antonietti *et al*., 2014).

Table 11. Mediating effect test analysis results based on GRD.

Variables	Mediation Effect Test Model Based on ECRR			Mediation Effect Test Model Based on GIA		
	ROE	GRD	ROE	ROE	GRD	ROE
	(1)	(2)	(3)	(4)	(5)	(6)
ECRR	-4.539***	-0.981	-4.990***			
	(-20.37)	(-0.85)	(-22.38)			
ECRRSq	30.361	0.644	30.609*			
	(1.43)	(1.08)	(1.45)			
GIA				0.851***	0.139**	0.812***
				(3.29)	(-4.82)	(4.91)
GIASq				-8.996339	-6.607	-9.235***
				(-1.38)	(0.68)	(-3.15)
GRD			-0.083			0.059***
			(-0.90)			(13.04)
SOE	0.012***	-0.043***	0.009***	0.010***	-0.047***	0.008***
	(5.87)	(-16.54)	(4.17)	(3.77)	(-17.38)	(3.54)
Lev	-0.234***	-0.072***	-0.240***	-0.208***	-0.026***	-0.210***
	(-49.43)	(-12.29)	(-50.77)	(-43.17)	(-4.37)	(-43.49)
ATO	0.012***	-0.052***	0.009***	0.066***	-0.021***	0.065***
	(5.14)	(-17.61)	(3.54)	(27.88)	(-7.53)	(29.12)
FirmAge	-0.020*	0.202***	-0.006*	-0.001***	0.237***	0.002
	(-7.96)	(59.39)	(-1.94)	(-6.09)	(68.82)	(0.75)
Mshare	0.010***	0.097***	0.017***	0.012***	0.118***	0.017***
	(2.97)	(14.92)	(3.25)	(2.82)	(17.26)	(3.12)
Herfindahl5	0.140***	-0.015	0.140***	0.168***	0.058***	0.171***
	(17.49)	(-1.51)	(17.51)	(17.17)	(5.67)	(20.72)
Mfg	-0.009	0.006**	-0.009***	-0.010***	0.007***	-0.009***
	(-4.66)	(2.34)	(-4.50)	(-3.54)	(2.86)	(-4.63)
Constant	0.250	0.105***	0.259***	0.096***	-0.135***	0.090***
	(24.85)	(8.45)	(25.84)	(12.36)	(-11.93)	(9.82)
Observations	31,411	31,411	31,411	30,317	30,317	30,317
R-squared	0.115	0.137	0.125	0.092	0.146	0.095

*Note: *** is correlated at the 1% level. ** is correlated at the 5% level. * is correlated at the 10%. The t-value is shown in parentheses.*

Based on this, this study introduces green technological R&D efficiency (GRD) as a mediating variable to test whether it plays a role in transmitting the effects of green investment and environmental expenses on business performance. The measurement of GRD is based on the slack-based model (SBM) in data envelopment analysis (DEA), which quantifies the input and output of firms to assess their efficiency in the green technology R&D phase. The inputs include the number of R&D personnel and R&D expenditure, while the outputs are measured by the number of green patent applications and green patents granted. These indicators are incorporated into the DEA-SBM model, which aims to minimize the slack variables in both inputs and outputs to compute the efficiency score for each firm. The mathematical formulation of the model can be expressed as follows:

$$\theta^* = min \quad \frac{1}{m}\sum_{j=1}^{m}\frac{s_j^-}{x_{kj}} + \frac{1}{r}\sum_{i=1}^{r}\frac{s_i^-}{y_{ki}} \tag{10}$$

$$\text{s.t.} \quad \sum_{j=1}^{n}\lambda_j x_j - s_j^- = \theta_{x_{0j}}, j = 1,2,\ldots,m$$

$$\sum_{j=1}^{n}\lambda_j x_j + s_j^+ = y_{0i}, i = 1,2,\ldots,r$$

$$\lambda_j \geq 0, j = 1,2,\ldots,n$$

$$s_j^- \geq 0, j = 1,2,\ldots,m$$

$$s_j^+ \geq 0, i = 1,2,\ldots,$$

In the Equation 11, θ* represents the firm's GRD score, while S_j^- and S_j^+ are the slack variables for inputs and outputs, respectively, indicating the amount by which inputs can be reduced or outputs can be increased at the current efficiency level. By solving the above model, we can obtain each firm's efficiency score θ* in the green technological R&D phase. The closer the score is to 1, the higher the firm's GRD.

In practical applications, considering the time lag in R&D activities, the initial investment, intermediate outputs, and final outputs of green innovation correspond to data from year t, year t+1, and year t+2, respectively. That is, when calculating a firm's GRD for a given year, it is necessary to use the input data from the previous year and the output data from the following year.

The test results are shown in **Table 11**. As can be seen from column (2), the coefficients of ECRR and ECRRSq are not significant at the 10% level. In column (3), the coefficient for GRD remains insignificant, indicating that GRD is not a mediating variable in the relationship between ECRR and ROE. From column (5), we can observe that the GIA coefficient is significantly positive, while the GIASq coefficient is not significant, suggesting that an increase in GIA directly promotes the improvement of GRD. In column (6), GRD is significantly positive, confirming its role as a mediating variable in the relationship between GIA and ROE, meaning that GIA enhances GRD, which in turn promotes the improvement of business performance.

Thus, in contrast to previous studies that use mixed low-carbon investments to test their impact on technological innovation (Liu *et al*., 2025; Feng *et al*., 2024; Liza *et al*., 2024), the conclusion here indicates that we cannot simply assume that a firm's low-carbon behaviors either inhibit or promote technological innovation. The effects of different types of low-carbon expenditures on business performance through technological innovation are not the same.

5.1.2. Green finance index

In accordance with modern financial theory, the financial decision-making and resource allocation efficiency of enterprises are key factors influencing corporate performance. As an emerging financial model, green finance directly impacts corporate green investment and environmental expenditure by providing financial support and optimizing resource allocation, thereby affecting their business performance. The Green Finance Index (GFI) is a comprehensive indicator used to measure the level of green financial development. The construction of the GFI typically encompasses multiple dimensions, such as green credit, green bonds, and green funds. Together, these indicators form a comprehensive evaluation system for assessing the performance and development level of a region or enterprise in the field of green finance. Numerous empirical studies have confirmed the significant impact of green finance on corporate performance. For example, Zhang *et al*. (2024) found that the green finance index is significantly positively correlated with corporate green innovation and environmental performance (Zhang *et al*., 2024). Liu *et al*. (2024) also pointed out that green finance significantly enhances corporate financial performance by optimizing resource allocation (Liu *et al*., 2024). **Table 12** provides a detailed display of the sub-indicators of the GFI.

Table 12. Indicators involved in GFI

Indicator	Variable	Calculation Formula
Green Credit Ratio	GCR	Ratio of green credit balance to total credit balance
Green Bond Ratio	GBR	Ratio of total green bond issuance to total bond issuance
Fiscal Support Ratio	GSR	Ratio of fiscal environmental protection expenditure to general fiscal budget expenditure
Green Fund Ratio	GFR	Ratio of total market value of green funds to total market value of all funds
Green Equity Ratio	GRE	Ratio of carbon trading, energy rights trading and pollution rights trading to total equity market transaction value

Green finance can alleviate corporate financing constraints by providing funding support, which promotes the effective use of green investments and environmental protection expenditures. Additionally, it can enhance environmental management levels by optimizing resource allocation, reducing environmental costs, and ultimately improving business performance. Furthermore, green finance directs capital flows toward green projects, enhancing a company's market reputation and social recognition, which in turn indirectly strengthens its sustainable development capacity. Therefore, GFI, as a mediating variable, can effectively reveal the transmission mechanism through which green investments and environmental protection expenditures, supported by green finance, influence business performance. The calculation formula for the GFI first determines the weight of each indicator using the entropy method.

$$P_{ij} = \frac{x^{'}}{\sum_{i=1}^{m} x^{'}} \tag{11}$$

$$e_j = -\frac{1}{lnm}\sum_{i=1}^{m} P_{ij} ln\left(P_{ij}\right) \tag{12}$$

$$d_j = 1 - e_j \tag{13}$$

$$w_j = \frac{d_j}{\sum_{i=1}^{m} d_j} \tag{14}$$

The GFI is calculated by integrating the standardized values of various indicators and their corresponding weights, as shown in Equation 15.

$$\text{GFI}=\sum_{j=1}^{n} w_j \times \text{x}_\text{j}' \tag{15}$$

The test results are shown in **Table 13**. As indicated in column (2), the ECRR coefficient is significantly negative, while the ECRRSq coefficient is significantly positive. This suggests a U-shaped relationship between ECRR and GFI, where an initial increase in ECRR exerts pressure on the company's liquidity, thereby restricting its ability to access green finance. This is because companies require time to adapt to new environmental requirements and demonstrate the effectiveness of their transformation efforts. However, as companies continue to invest in environmental protection and implement green projects, they gradually exhibit stronger green competitiveness and market recognition, which, in turn, fosters trust and support from green finance institutions, thus increasing the likelihood of securing green finance. As shown in column (3), the GFI coefficient is significantly positive, indicating that green finance can significantly enhance business performance. The ECRR and ECRRSq coefficients are significant at the 1% level, suggesting that green finance acts as a mediating variable in the relationship between environmental protection expenditures and business performance, playing a mediation role.

In column (5), the GIA coefficient is significantly positive, while the GIASq coefficient is significantly negative, indicating that the initial increase in green investment can promote the growth of green finance support because financial institutions are more willing to finance green projects. However, once green investment reaches a certain level, the positive impact on green finance diminishes or even turns negative due to reduced resource allocation efficiency or market saturation. Additionally, excessive green investment may occupy too much productive capital, negatively affecting the company's financial health and reducing its ability to attract green finance. This relationship underscores the importance of adhering to a principle of moderation when promoting green investment to avoid resource waste and efficiency decline. As shown in column (6), the GFI coefficient is significantly negative in relation to ROE, suggesting that although green finance is intended to support green projects, it may not effectively translate into improved business performance in practice, or the investment returns from green finance may be relatively low. In this process, the GIA and GIASq coefficients are significant at the 1% level, indicating that GFI mediates the effect of GIA on ROE, playing a mediating role.

Table 13. Mediating effect test analysis results based on GFI

Variables	**Mediation Effect Test Model Based on ECRR**			**Mediation Effect Test Model Based on GIA**		
	ROE	**GFI**	**ROE**	**ROE**	**GFI**	**ROE**
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
ECRR	-4.539***	-5.416***	-5.111***			
	(-20.37)	(-19.81)	(-22.94)			
ECRRSq	30.361	54.279***	31.897***			
	(1.43)	(12.62)	(9.13)			
GIA				0.851***	0.139	0.812***
				(3.29)	(0.68)	(4.91)
GIASq				-8.996339	-6.607*	-9.235***
				(-1.38)	(-1.82)	(-3.15)
GFI			0.096***			-0.059***
			(21.81)			(-13.04)
SOE	0.012***	-0.044***	0.008***	0.010***	-0.047***	0.007***
	(5.87)	(-16.70)	(3.94)	(3.77)	(-17.50)	(3.33)
Lev	-0.234***	-0.067***	-0.241***	-0.208***	-0.025***	-0.210***
	(-49.43)	(-11.46)	(-51.12)	(-43.17)	(-4.29)	(-43.59)
ATO	0.012***	-0.047***	0.007***	0.066***	-0.019***	0.065***

	(5.14)	(-15.67)	(3.07)	(27.88)	(-6.89)	(29.01)
FirmAge	-0.020*	0.197***	-0.003	-0.001***	0.234***	0.005
	(-7.96)	(58.19)	(-0.94)	(-6.09)	(68.01)	(1.60)
Mshare	0.010***	0.081***	0.020***	0.012***	0.104***	0.019***
	(2.97)	(12.43)	(3.74)	(2.82)	(15.31)	(3.45)
Herfindahl5	0.140***	-0.007	0.140***	0.168***	0.065***	0.171***
	(17.49)	(-0.67)	(17.43)	(17.17)	(6.35)	(20.77)
Mfg	-0.009	0.004*	-0.008***	-0.010***	0.006**	-0.009***
	(-4.66)	(1.73)	(-4.41)	(-3.54)	(2.19)	(-4.56)
Constant	0.250	0.107***	0.260***	0.096***	-0.122***	0.088***
	(24.85)	(8.66)	(25.99)	(12.36)	(-10.81)	(9.61)
Observations	31,411	31,411	31,411	30,317	30,317	30,317
R-squared	0.115	0.128	0.128	0.092	0.141	0.096

*Note: *** is correlated at the 1% level. ** is correlated at the 5% level. * is correlated at the 10%. The t-value is shown in parentheses*

The results of the mediation analysis regarding ECRR and GIA in the transmission of GFI effects reveal distinct differences in their impact on business performance. The path analysis further confirms that the effect of environmental protection expenditures on business performance is primarily negative, without a process of qualitative transformation driven by quantitative change. Unlike GIA, the increase in ECRR before reaching the inflection point not only fails to promote technological innovation within the company but also impedes its ability to secure green finance, thereby reducing business performance. Only sustained investment in environmental protection can build trust and support from green finance institutions, increasing the likelihood of securing green finance. Therefore, companies should prioritize green investment expenditure strategies to achieve a win-win scenario for both environmental and economic benefits. Based on the above analysis, the policy recommendations at the company level are illustrated in **figure 3**.

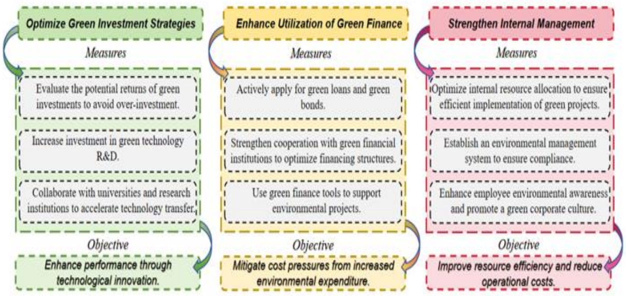


Figure 3. Enterprise-level policy recommendations based on mediation effect test analysis

5.2. Heterogeneity analysis

In the previous section, a systematic analysis was conducted from multiple perspectives to explore the specific transmission mechanisms of low-carbon behaviors, such as green investment, on corporate performance. To further investigate the intrinsic mechanisms through which corporate environmental expenditures influence business performance, this section systematically analyzes and compares the unique challenges and potential opportunities that companies face in their low-carbon transformation from the dual perspectives of ownership structure and industry differences. Through multidimensional heterogeneity analysis, this study not only extends the existing theoretical framework but also provides new empirical evidence and theoretical support for companies to develop differentiated environmental strategies.

Specifically, environmental expenditures are often closely related to the corporate ownership structure and governance mechanisms. SOEs tend to show a higher level of enthusiasm in environmental protection expenditures due to their special policy orientation and social responsibility requirements. This tendency is closely related to their ownership structure. Therefore, in Section 5.2.1, a heterogeneity analysis of environmental expenditures based on ownership structure is conducted. On the other hand, the effectiveness of green investment mainly depends on the industry characteristics, as different industries exhibit significant differences in the demand for green technologies and market potential. These differences directly impact the benefits of green investment and its effect on corporate performance across industries. Given this, Section 5.2.2 further conducts a heterogeneity analysis of green investment based on industry attributes to uncover its role and impact mechanisms in various industries.

5.2.1. Heterogeneity test of ECRR Based on ownership structure

The results presented in columns (1) and (2) of **Table 14**, as well as in **figure 4(a)**, clearly show that both SOEs and NSOEs exhibit a downward trend in business performance with the increase in environmental expenditures. However, the decline in performance for NSOEs is significantly larger than that of SOEs, further supporting the validity of Hypothesis 3.

Given the significant differences in business performance changes under increasing environmental expenditures across different ownership structures, this finding provides a basis for formulating differentiated low-carbon strategies in environmental expenditure policies. For SOEs, their advantages in resource acquisition and policy support provide them with greater resilience when facing increased environmental costs. Therefore, SOEs should leverage these advantages to further increase investment in green technological innovation and cleaner production to achieve both environmental and economic benefits.

Simultaneously, SOEs should actively explore ways to optimize resource allocation, such as internal capital reallocation and asset restructuring, to more effectively mitigate the financial risks arising from rising environmental costs. In contrast, NSOEs face greater challenges when confronted with rising environmental expenditures, with a more pronounced decline in business performance. As a result, NSOEs need to focus more on optimizing internal resource allocation, improving resource utilization efficiency, and reducing operational costs to alleviate the pressure caused by increased environmental expenditures. For instance, NSOEs can enhance their resource acquisition and risk management capabilities by introducing strategic investors or collaborating with other companies (Zhang *et al*., 2024). Moreover, NSOEs should actively seek external support, such as participating in green finance projects or applying for environmental protection funds to obtain financial assistance (Zhang *et al*., 2025; Gao *et al*., 2024).

5.2.2. Heterogeneity test of GIA based on industry affiliation

The differences in resource consumption and carbon emission intensity are the fundamental reasons for the varying low-carbon behaviors between the manufacturing and non-manufacturing sectors. These differences not only determine the urgency of implementing low-carbon behaviors but also influence the internal motivation and strategic choices of enterprises. Therefore, we choose to conduct a heterogeneity analysis based on industry attributes, focusing solely on whether a company belongs to the manufacturing sector.

The results presented in columns (3) and (4) of **Table 14**, as well as in **Figure 4(b)**, clearly demonstrate that with the increase in GIA, the business performance of manufacturing enterprises shows a significant improvement. In contrast, for non-manufacturing enterprises, the benefits of green investment are not apparent, and their business performance even shows a slow decline. Manufacturing enterprises typically have higher resource consumption and carbon emission intensity, which means that green investment can directly reduce production costs and improve production efficiency, leading to a rapid transformation into improved business performance. In contrast, non-manufacturing enterprises have lower resource consumption and carbon emission intensity, so green investment does not produce significant direct benefits in the short term. Its impact on business performance is more dependent on the market environment and consumer preferences. Thus, Hypothesis 4 is confirmed.

Table 14. Results of heterogeneity test

Variables	Nature of property rights		Industry Affiliation	
	SOEs	**NSOEs**	**Manufacturing firm**	**Non-manufacturing firm**
	(1)	(2)	(3)	(4)
ECRR	-7.520***	-11.07***		
	(-14.26)	(-25.71)		
ECRRSq	69.93***	86.50***		
	(8.87)	(15.06)		
GIA			0.274	-0.0657
			(1.22)	(-0.17)
GIASq			5.743	0.0476
			(1.49)	(0.01)
Lev	-0.322***	-0.403***	-0.350***	-0.435***
	(-25.55)	(-37.61)	(-35.79)	(-24.70)
ATO	0.0424***	-0.0252***	0.129***	0.0711***
	(6.55)	(-3.96)	(23.45)	(8.36)
FirmAge	0.0858***	0.0921***	0.0621***	0.131***
	(3.94)	(4.53)	(3.42)	(4.55)
Mshare	-0.137	0.0340*	0.0705***	0.115***
	(-1.64)	(2.56)	(5.30)	(3.61)
Herfindahl5	0.0944***	0.208***	0.191***	0.190***
	(3.89)	(7.89)	(8.41)	(4.83)
Mfg	-0.0443***	0.0354***		
	(-5.06)	(4.59)		
SOE			-0.0223***	-0.00208
			(-3.16)	(-0.16)
CONSTANT	0.0787	0.125*	0.0787	0.137
	(1.37)	(2.45)	(-1.75)	(-1.82)
N	12013	21968	22405	9961

*Note: *** is correlated at the 1% level. ** is correlated at the 5% level. * is correlated at the 10%. The t-value is shown in parentheses.*

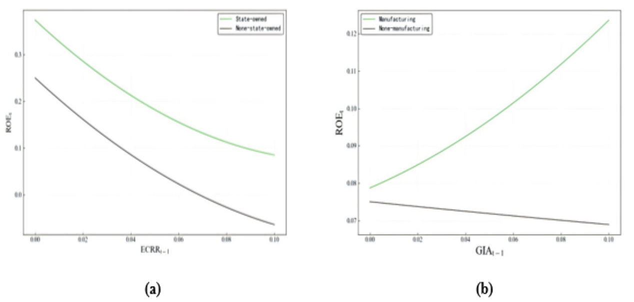


Figure 4. Regression outcomes of variables after heterogeneity assessment: (a) Based on different property rights properties; (b) Based on different industry attributes

Based on the above analysis, when formulating low-carbon strategies, enterprises should fully consider their industry attributes and resource characteristics. For manufacturing enterprises, it is important to increase green investment by adopting clean production technologies, optimizing production processes, and improving energy efficiency to achieve resource conservation and cost reduction. This not only improves their own business performance but also promotes the sustainable development of the entire industry. In addition, manufacturing enterprises should focus on industry chain integration and synergy, promoting upstream and downstream companies to jointly implement environmental measures, thereby creating a green supply chain and enhancing the competitiveness of the entire industry. For non-manufacturing enterprises, while green investment may not produce significant direct benefits, these enterprises must still recognize the importance of green transformation (Zhao *et al*., 2024). Non-manufacturing enterprises should first focus on improving their operational efficiency and core competitiveness, ensuring steady development, and gradually advancing green transformation. For example, non-manufacturing enterprises can enhance their market competitiveness and brand image by introducing green office concepts, promoting energy-saving and environmentally friendly products, and strengthening interaction with consumers (Li *et al*., 2024).

The heterogeneity analysis results indicate that different types of enterprises face distinct challenges and opportunities during their low-carbon transformation, highlighting the importance of formulating tailored low-carbon strategies based on enterprise types and industry characteristics. On this basis, **figure 5** systematically organizes differentiated strategies for various types of enterprises and industry characteristics, aiming to provide more targeted guidance for enterprises in their low-carbon transformation process.

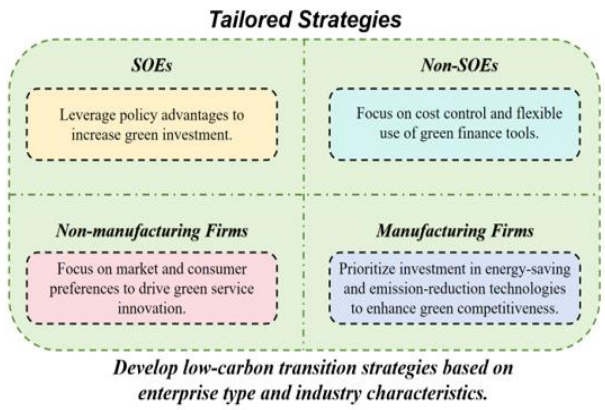


Figure 5. Targeted guidance for enterprises in the low-carbon transformation process

6. Conclusion

This study systematically examines the relationship between corporate low-carbon behavior and operational performance among Chinese listed companies, distinguishing between ECRR and GIA and revealing their distinct impacts. The findings indicate that while environmental expenditures may impose short-term financial burdens, sustained environmental investments can enhance corporate green competitiveness and attract green financial support, thereby effectively mitigating negative impacts. In contrast, green investments exhibit an inverted U-shaped relationship with performance: moderate green investments can promote corporate innovation capabilities and operational efficiency, whereas excessive investments lead to diminishing returns. These conclusions provide important insights for refining ESG investment standards and optimizing carbon pricing mechanisms, further enriching and expanding the existing theoretical framework.

From the perspective of policymakers, the model underscores the necessity of constructing a differentiated policy framework. Introducing thresholds in carbon pricing mechanisms can effectively avoid resource wastage and inefficiencies caused by excessive investments. Meanwhile, tailoring subsidies or tax incentives according to industry characteristics can encourage companies to engage in optimal levels of green investment, with particularly significant returns observed in the manufacturing sector. Additionally, policies supporting green finance initiatives, such as providing preferential loans to SOEs or small and medium-sized enterprises, can effectively alleviate corporate resource constraints and further amplify the positive effects of environmental expenditures. From a societal perspective, the study advocates the use of transparent ESG indicators to clearly differentiate between ECRR and GIA. Investors and regulatory authorities can utilize these findings to refine ESG rating systems, prioritizing support for companies that achieve a balance between environmental commitment and economic feasibility. By integrating corporate low-carbon strategies with broader sustainable development goals, the model helps to drive corporate green transformation and promote a more equitable and efficient transition to a low-carbon economy.

In summary, through systematic empirical analysis, this study reveals the complex relationship between corporate low-carbon behavior and operational performance, as well as the underlying mechanisms. However, this study focuses solely on the unique institutional and regulatory environment of Chinese companies. While its findings provide critical insights for China's low-carbon transition, their generalizability remains to be verified. Future research should conduct cross-country comparisons to assess how differences in policy frameworks, market structures, and cultural norms across countries and regions affect the effectiveness of low-carbon strategies, thereby further enriching and perfecting the relevant theoretical frameworks.

Declaration of competing interest

The authors declare no conflicts of interest.

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