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Research article

State-owned capital and quality of green innovation: Evidence from Chinese listed private firms

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ABSTRACT

Green innovation is pivotal for global sustainability, with state-owned capital playing a significant role, especially in the Chinese corporate landscape. This study, spanning 2008 to 2020 and leveraging a comprehensive dataset of listed companies, explores the intricate relationship between state-owned capital and the quality of green innovation in Chinese private enterprises. Motivated by the imperative to address crucial issues in green innovation quality in China, this research utilizes empirical data to uncover the mechanisms through which state-owned capital fosters green innovation. The study reveals how state-owned capital optimizes internal governance structures and reinforces environmental consciousness within private firms. Findings underscore the crucial role of state-owned capital in enhancing the quality of green innovation in private enterprises, operating through two primary mechanisms. Firstly, state-owned capital cultivates a heightened inclination towards green innovation within these firms. Secondly, it facilitates the adoption of enhanced internal governance practices, catalyzing the development of high-quality green innovation projects. A battery of mechanism tests provides robust evidence that state-owned capital enhances environmental awareness, restrains self-serving behaviors among major shareholders, mitigates financing constraints, and amplifies the motivation and capability of private enterprises for green innovation. This multifaceted approach ultimately fosters high-quality green innovation within companies. The study reveals the subtle interplay between state capital and private sector green innovation, highlighting its relevance to policy-making and practical considerations. It provides valuable insights into the ongoing pursuit of sustainability and the integration of green practices into the corporate world.

1. Introduction

In the dynamic landscape of business innovation, the pursuit of green practices has emerged as a crucial strategy for enterprises worldwide. Green innovation, denoting the proactive measures taken by businesses to enhance resource efficiency, curb pollutant emissions [1,2], and embed environmental considerations into product design and production processes, represents a paradigm shift aimed at mitigating the negative environmental impact of products [3–5]. This transformative approach not only aims to boost the economic and environmental performance of enterprises through innovative practices [6–9] but also plays a pivotal role in shaping their green brand image and securing higher legitimacy.

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While the merits of green innovation, including improved stock returns and financial performance [10–12], are well-documented, recent research unveils a nuanced reality [2,4,13–15]. Not all green innovations uniformly contribute to firm value [1,10]. External soft regulations [16], under the influence of which many companies intensify the quantity of green innovation [17], may inadvertently sideline the crucial aspect of innovation quality, leading to a limited improvement in economic value [18–20]. External soft regulations, under the influence of which many companies intensify the quantity of green innovation, may inadvertently sideline the crucial aspect of innovation quality, leading to a limited improvement in economic value [2,12,21]. Scholars highlight the indispensable nature of high-quality innovation in enhancing firm value, underscoring the need to holistically consider both "quality" and "quantity" for superior innovation outcomes. Thus, the imperative to enhance the quality of green innovation in private enterprises becomes paramount for fostering competitiveness and promoting high-quality development.

Beyond individual enterprises, the global community faces an urgent need to address climate change and mitigate the impact of global warming. The concept of the "Dual Carbon" goal, encapsulating both carbon peak and carbon neutrality, has gained significance [17,22]. Across the globe, nations and organizations are formulating plans and taking action to achieve these goals, acknowledging the imperative to reduce their impact on the climate system [23,24]. In September 2020, General Secretary Xi of China articulated an ambitious goal for the nation to peak carbon dioxide emissions before 2030 and achieve carbon neutrality by 2060 [25,26]. This declaration not only reflects China's commitment as a responsible major country in global climate governance but also charts a new direction for its economic and social development [27]. The 20th National Congress of the Communist Party further solidified this commitment by incorporating stabilizing carbon emissions after peaking into the overall development goals for 2035 [27–29]. Emphasizing the need for a green transformation of development patterns, comprehensive conservation strategies, and the development of green and low-carbon industries, this directive outlines a multifaceted approach to address climate change [8,9,30,31].

Within this global context, green innovation takes center stage, encompassing the development and adoption of environmentally friendly technologies, practices, and products. Private enterprises, serving as the main drivers of green innovation, play a vital role in propelling not only China's green development but also contributing to global sustainability. Consequently, the promotion of green innovation in private enterprises holds immense practical significance [14,32,33]. As the predominant force representing over 90% of China's business entities, private enterprises serve not only as crucial drivers of green innovation but also as significant contributors to energy conservation, emission reduction, and carbon mitigation [34,35]. The transition towards green and low-carbon practices aligns with the broader trend of achieving high-quality economic development and presents an opportunity for private enterprises to enhance their market competitiveness. This shift not only constitutes a pivotal measure in propelling economic structural adjustments but also represents an inevitable choice for private enterprises to fulfill their social responsibilities. In the Chinese Research Data Services Platform (CNRDS) database, data related to green innovation of private enterprises were discovered (refer to Fig. 1). From 2008 to 2014, the number of green patents applied for by Chinese privately listed companies grew slowly, from 77 to 2192. Starting in 2015, there was an explosive growth in green patents, reaching a peak of 12,200 in 2019. Looking at the citation frequency of green patents of private enterprises within two years, it can be observed that from 2008 to 2017, the citation frequency of patents increased synchronously with the number of green patent applications. However, starting from 2018, there was a cliff-like decline. This indicates that although Chinese private enterprises have been actively engaged in green innovation since 2018, the number of citations for patents has decreased significantly, indicating that the quality of green patents of enterprises has not improved significantly and even shows a downward trend. The data above suggest that there may be a certain bubble phenomenon in current green innovation of

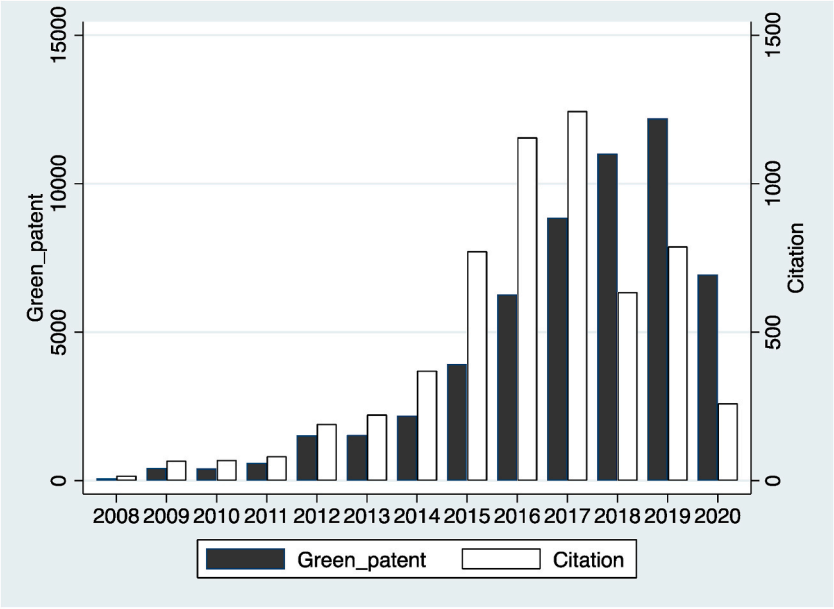

Fig. 1. Green patent applications by Chinese privately listed companies from 2008 to 2020.

Chinese private enterprises, with a surge in the number of patents but a decline in patent quality. These two indicators represent the sum of corresponding indicators for all private enterprises in China each year. From the data, it can be seen that there is a practical problem of 'quantity over quality' in enterprise green innovation. In Fig. 1, Green_patent represents the total number of green patents applied for by private enterprises each year (representing quantity indicators), while Citation represents the total frequency of green patent applications by private enterprises cited in the next two years (representing quality indicators).

The China Private Enterprises Green Development Report (2022), based on survey data from 10,623 Chinese private enterprises, reveals that approximately 30% of private industrial enterprises have formulated implementation plans related to the "peak carbon emissions" and "carbon neutrality" initiatives. Moreover, 53.5% of private enterprises in high-energy-consuming industries have established dedicated departments responsible for energy conservation and carbon reduction, actively applying decarbonization technologies. Guided by green development objectives, an increasing number of private enterprises are realigning their development models from "high energy consumption, high pollution, and high emissions" to a green, low-carbon, and circular development paradigm. In the list of the top 500 private enterprises in China for the year 2022, 426 companies actively participated in the nationwide campaign against pollution. But the current challenges in China's green innovation landscape, specifically the prevalence of lightweight green innovation [36–38]. Recognizing the synergistic relationship between innovation quantity and quality, the introduction underscores the importance of balancing both aspects for optimal innovation outcomes. How can the internal motivation for green innovation in private enterprises be enhanced to achieve high-quality outcomes? This question serves as the driving force behind our study, addressing a crucial issue that urgently requires resolution.

Existing research has predominantly focused on the influencing factors of green innovation output, often neglecting the critical aspect of enhancing innovation quality [39]. The synergistic relationship between innovation quantity and quality presents a challenge for enterprises striving for high-quality development [40], with scholars pointing out that existing external environmental regulations may not adequately stimulate intrinsic motivation for green innovation in private enterprises [41,42]. Consequently, addressing how to enhance the internal driving forces for green innovation in private enterprises and achieve high-quality outcomes becomes an urgent issue, not limited to any specific geographic region. In the pursuit of this imperative, state-owned capital emerges as a key player, representing the economic manifestation of the national governance system, with objectives aligning with national strategies [39,43]. Guided by China's green development strategy, state-owned capital not only possesses the social objective of promoting the green development of enterprises but also functions as a potent internal governance mechanism within these enterprises [41,44,45]. The infusion of state-owned capital into private enterprises holds the potential to integrate national goals of green development into corporate decision-making, leverage its internal governance role, stimulate green innovation dynamics, and enhance the quality of green innovation.

Building on existing research, this paper aims to explore the impact of state-owned capital infusion on the quality of green innovation in private enterprises and unveil its underlying mechanisms. Our study addresses the following key questions: Firstly, what is the relationship between state-owned capital infusion and the quality of green innovation in private enterprises? Secondly, through what mechanisms does state ownership influence the quality of green innovation in private enterprises? Thirdly, as an internal governance mechanism, does the impact of state-owned capital infusion on the quality of green innovation in private enterprises differ under different external supervision environments? Focusing on A-share privately listed companies on the Shanghai and Shenzhen stock markets from 2008 to 2020, our findings suggest that state-owned capital infusion positively impacts the internal dynamics of green innovation in private enterprises. It facilitates improvements in internal governance, leading to an enhancement in the overall quality of green innovation. The mechanism analysis reveals that state-owned capital achieves this by reinforcing environmental consciousness, curbing "greenwashing" motives, and inhibiting opportunistic behaviors among major shareholders, ultimately promoting high-quality green innovation. Additionally, state-owned capital contributes to alleviating financing constraints, reducing resource burdens on innovation, and boosting the overall green innovation capabilities of private enterprises. Our study uncovers variations in the influence of state-owned capital on the quality of green innovation under different external supervisory environments, ensuring the robustness and consistency of our research conclusions.

The potential theoretical contributions and practical significance of this study extend beyond China and resonate globally, particularly in developing countries. Firstly, in conjunction with China's vigorous promotion of the mixed-ownership reform, this paper explores the impact of 'reverse mixed-ownership reform' on the green innovation activities of private enterprises. By thoroughly discussing the antecedents of corporate green innovation quality from the perspective of corporate ownership structure, we address the limitations in current research that lacks sufficient attention to green innovation quality. Secondly, our study reveals in-depth the mechanisms through which state-owned capital affects the green innovation quality of private enterprises, enriching related studies on the economic consequences of changes in ownership structure and the antecedents of corporate green innovation quality. Additionally, it unveils the boundary conditions of the impact of state-owned capital on the green innovation quality of private enterprises from an external governance perspective. Thirdly, our conclusions indicate that the entry of state-owned shareholders can stimulate the green innovation drive of private enterprises, enhance the green innovation capabilities of private enterprises, and thus improve the green innovation quality of private enterprises.

This perspective of 'reverse mixed-ownership reform' enriches relevant research on corporate reform. In essence, our study transcends geographical boundaries, offering insights that can benefit other similar system countries worldwide, especially for those in the developing world where state-owned capital participates in green innovation within private enterprises. By emphasizing the implications of our findings, the research on green innovation quality holds global significance and far-reaching benefits, particularly for developing countries. Green innovation contributes to sustainable development by reducing environmental impact and fostering cleaner production practices. The transfer of environmentally friendly technologies, capacity building, and a focus on market competitiveness create new opportunities for developing nations in the global green economy [46,47]. Furthermore, such research

plays a vital role in mitigating climate change. Insights derived from the study can inform effective policy frameworks, offering practical guidance for developing countries striving to achieve sustainable development goals on a global scale. Thus, the implications of this research extend well beyond China, offering valuable contributions to the broader international community.

The remainder of this paper is organized as follows. The second section establishes the theoretical foundation and research hypotheses, analyzing the mechanisms through which state-owned capital enhances the quality of green innovation in private enterprises. The third section presents the research design, including sample selection and data sources, variable definitions, research methods, and model specifications. The fourth section presents empirical results and discusses the analysis, including descriptive statistics, regression analysis, and robustness tests across three aspects. The fifth section analyzes the heterogeneous effects of private enterprises, including social supervision and institutional oversight. The sixth section concludes with insights and limitations, as well as future prospects.

2. Literature and hypotheses

2.1. Literature review

Based on the existing studies, it is challenging to stimulate the motivation for green innovation and improve the quality of green innovation in enterprises, whether through flexible regulatory measures, mandatory requirements, or policy support for innovation activities. Existing research has primarily explored the factors influencing the quality of green innovation in Chinese enterprises from the perspectives of external environmental regulations [13], internal characteristics [48], enterprise transformation and upgrading [49–52]. Only by internally stimulating the motivation for green innovation can the quality of green innovation be fundamentally enhanced [12,21,53]. However, existing research mainly focuses on the impact of external environmental regulations on the quality of green innovation [13], with limited attention given to the internal characteristics of enterprises. Therefore, how to promote private enterprises to improve the quality of green innovation from within is an important question of both theoretical and practical significance, and it is the purpose of this study.

State-owned capital, as an important internal governance mechanism, contributes to promoting high-quality development in private enterprises. Firstly, the political connections generated by state shareholders can enhance the financing convenience of private enterprises [10,18], alleviate financing constraints [1,12], and increase the level of cash holdings [54], thereby mitigating the problem of insufficient investment in private enterprises [55], stimulating innovation inputs in private enterprises [56], and improving firm performance [4,57,58]. Secondly, state shareholders have strong social objectives [59,60] and, backed by the national context, they can fully utilize their supervisory mechanisms in private enterprises [61], balancing the strong profit-seeking motives of private enterprises and enhancing their social responsibility performance [2,5]. For example, they can increase employment the opportunities provided by private enterprises [62,63], curb tax evasion behaviors of private enterprises, and improve the level of environmental responsibility in private enterprises [64,65].

Existing research confirms that the introduction of state-owned capital is an effective approach for private enterprises to achieve high-quality development with the support of state resources [14,58]. However, can state-owned capital infusion also stimulate the intrinsic green innovation drive in private enterprises and enhance the quality of their green innovation? Although scholars have explored the impact of state-owned capital infusion on green innovation in private enterprises from the perspective of mixed-ownership reform [12], this research has only discussed the influence of state-owned capital on the green innovation activities of private enterprises from the dimension of innovation output, neglecting the crucial aspect of green innovation quality. Therefore, this study aims to investigate the influence of state-owned capital infusion on the green innovation quality of private enterprises from the perspective of mixed-ownership reform, and to delve into the underlying mechanisms and boundary conditions. Specifically, this article argues that state-owned capital infusion can enhance the green innovation quality of private enterprises by stimulating their green innovation drive and strengthening internal supervision. In terms of mechanisms, state-owned capital infusion primarily improves the green innovation quality of private enterprises through two pathways: enhancing their environmental awareness and curbing opportunistic behavior of major shareholders.

2.2. State-owned capital and green innovation quality

Insufficient green innovation quality in private enterprises can be attributed to two main reasons. Firstly, private enterprises perceive green innovation as a superficial "green" tool to alleviate external environmental regulatory pressures. The promotion of green innovation in private enterprises is primarily achieved through external pressure from regulatory requirements, leading to a situation where innovation is pursued not to enhancing competitiveness but rather to comply with external policy demands by increasing innovation quantity and speed [66]. This approach fails to stimulate intrinsic green innovation drive within private enterprises, resulting in a lack of willingness to engage in high-quality green innovation. The infusion of state-owned capital transforms the government from a distant stakeholder to a corporate shareholder, thereby increasing the importance private enterprises attach to the government objectives [67,68]. Consequently, under the guidance of national green development strategies, the business objectives of private enterprises shift towards environmental benefits, thereby stimulating intrinsic green innovation drive within the enterprises [33,63].

Secondly, private enterprises perceive green innovation as a tool for "arbitrage" to acquire external resources [14]. By increasing the quantity of green innovation, private enterprises signal their commitment to external stakeholders such as investment institutions and government in order to obtain financial support [27,69,70]. However, due to information asymmetry, external stakeholders find it

challenging to quickly assess the quality of green innovation within a short period, leading them to rely on observable indicators (such as the number of patents) to determine their investment level in the enterprise [69]. Consequently, improving green innovation quality not only fails to help private enterprises obtain excess returns from external stakeholders but also increases research and development costs [48,71], contradicting the profit-driven motivation of private enterprises. This results in opportunistic behavior during the green innovation process, where private enterprises engage in low-quality, high-quantity green innovation to extract more external resources.

State-owned capital infusion can create a diversified equity structure with non-state-owned capital, thereby improving the internal governance environment of the enterprise. On one hand, the presence of state-owned shareholders can balance the economic and social objectives of private enterprises, restraining their motivation to exploit green innovation incentive policies for arbitrage. On the other hand, state-owned shareholders can exercise supervision within the enterprise, effectively regulating corporate activities [12,72], thereby reducing information asymmetry between the government and private enterprises, minimizing arbitrage behavior by private enterprises during the green innovation process, and emphasizing innovation quality.

Private enterprises often face challenges in obtaining advantages in national resource allocation due to their lack of political status and relatively lower market position. This difficulty in accessing favorable resource allocation hinders their ability to secure the financial support required for high-quality green innovation. State-owned capital infusion addresses this issue by promoting the green transformation of private enterprises through direct investments and providing a stable political connection, allowing businesses to establish reliable implicit guarantees from official entities [73–75]. This, in turn, enables enterprises to acquire more economic resources from the external environment, alleviating the resource constraints in the process of green innovation and empowering them to engage in high-quality green innovation.

In summary, state-owned capital infusion can, by adjusting corporate operational objectives, strengthen internal supervision, prompting responsible green innovation activities by private enterprises. Simultaneously, through resource effects, it enhances the green innovation capabilities of enterprises, ultimately elevating the quality of green innovation activities [15,76]. This study believes that state-owned capital primarily improves the green innovation quality of private enterprises through three pathways: enhancing environmental responsibility, optimizing internal governance, and mitigating financing constraints [77,78]. Based on the analysis above, this study proposes the following hypothesis.

H1. *State-owned capital participation can enhance the green innovation quality of private enterprises.*

2.3. State-owned capital, environmental consciousness, and green innovation quality

Inherent profit-driven motives make private enterprises prioritize investment returns, resulting in a lack of intrinsic motivation to fulfill environmental responsibilities. While external environmental regulations can induce companies to fulfill environmental responsibilities through green innovation, the social benefits derived from green innovation far outweigh the economic benefits for enterprises. This contradiction between the business objectives of private enterprises and the social benefits of green innovation undoubtedly leads to instrumental motivations for fulfilling responsibilities, rather than a genuine concern for social benefits. In other words, private enterprises, to maximize economic benefits, may opt for superficial green innovation with lower research and development costs, thereby enhancing short-term green innovation performance to alleviate external environmental regulatory pressures. Ultimately, this approach leads to insufficient green innovation quality in enterprises.

State-owned capital participation helps strengthen the environmental consciousness of private enterprises, thereby stimulating their green innovation drive and improving the quality of green innovation. J. KALER [68] argues that companies bear full responsibility to their shareholders, and the entry of state-owned capital transforms the government from a distant stakeholder to a shareholder [68]. State-owned shareholders share strategic goals with the government, which include preserving and increasing the value of state-owned assets while also considering social objectives such as environmental governance. Therefore, the participation of state-owned shareholders enhances the emphasis of private enterprises on social benefits, contributes to an enhanced sense of social responsibility, reinforces environmental consciousness within the company, and stimulates the intrinsic motivation for green innovation. This encourages enterprises to consider environmental benefits in their operations and actively engage in responsible green innovation, ultimately enhancing the quality of green innovation. Based on the analysis above, the following hypothesis is proposed.

H2. State-owned capital participation can enhance the green innovation quality of private enterprises by strengthening their environmental consciousness.

2.4. State-owned capital, controlling shareholders' self-serving behavior, and green innovation quality

Private enterprises are characterized by a high concentration of equity, granting controlling shareholders absolute control advantages. This concentration of equity provides controlling shareholders with strong self-serving motivations and facilitates the diversion of corporate resources. Under the influence of self-serving motivations, controlling shareholders may view green innovation as a tool for arbitrage. Specifically, as the government's attention to green development increases, numerous subsidies and tax policies are introduced to promote corporate green transformation [1,10,79]. However, the evaluation system for green innovation quality in China is not yet mature, and relevant authorities often measure the level of green innovation in terms of output, which facilitates policy arbitrage for companies by increasing short-term green innovation output. This may lead to private enterprises' controlling shareholders sacrificing innovation quality to lower research and development costs, maximizing their arbitrage opportunities. Furthermore, due to inadequate internal governance mechanisms, the resources obtained by private enterprises through "arbitrage-style"

green innovation are not reinvested in green innovation activities but instead become a "feast" for the controlling shareholders. Therefore, the self-serving behavior of controlling shareholders may restrict the improvement of green innovation quality in private enterprises in terms of motivation and resource allocation.

State-owned capital investment can establish a diversified ownership structure alongside existing private capital, thereby improving the internal quality of private enterprises, mitigating internal agency problems, and ultimately enhancing the quality of green innovation. On one hand, compared to external environmental regulations imposed by the government, state-owned capital investment can effectively reduce the information asymmetry between private enterprises and the government from within. This enables relevant authorities to exercise effective supervision over companies' green innovation and other business activities, thus restraining the self-serving motives of controlling shareholders and reducing opportunistic behavior during the green innovation process. As a result, it increases the level of attention private enterprises give to innovation quality. On the other hand, unlike other small and medium shareholders, state-owned shareholders can serve as an effective check and balance on controlling shareholders by leveraging their national background [72]. This helps curb the expropriation behavior of controlling shareholders. The balancing role of state-owned shareholders not only prevents the outflow of company resources but also avoids the inappropriate use of policy subsidies by controlling shareholders. It liberates strategic resources that have long been controlled by controlling shareholders. Consequently, private enterprises can allocate more resources to green innovation activities based on the social objectives of state-owned shareholders, thereby enhancing their green innovation capabilities and improving the quality of green innovation.

In summary, state-owned capital investment can effectively alleviate the second type of agency problem within private enterprises, weaken the self-serving motives of controlling shareholders, restrain their expropriation behavior, and enhance the focus of companies on green innovation quality. It also strengthens the green innovation capabilities of enterprises. Ultimately, it leads to an improvement in the quality of green innovation in private enterprises. Based on the analysis above, the following hypothesis is proposed in this study.

H3. State-owned capital investment can enhance the quality of green innovation in private enterprises by suppressing the self-serving behavior of controlling shareholders.

2.5. State-owned capital, financing constraints and green innovation quality

Green innovation is characterized by high risks and significant investments, and the pursuit of high-quality green innovation undoubtedly increases research and development (R&D) risks and costs. However, most private enterprises lack sufficient resources to sustain long-term R&D activities. Therefore, they need to obtain external resource support through financing and other means to drive innovation. Unfortunately, private enterprises often face financing discrimination due to the lack of political background, placing them at a natural disadvantage in national resource allocation and leading to the dilemma of "difficulty in financing." This presents a significant challenge to the realization of high-quality green innovation activities by enterprises.

State-owned capital infusion can assist private enterprises in establishing strong political connections, enhancing their ability to access external resources, and thus alleviating their financing difficulties [61,80,81]. On one hand, state-owned capital establishes connections between private enterprises and the government, helping to weaken the policy discrimination that private enterprises face in resource allocation. This, in turn, enables them to acquire more external resources. For example, political connections can assist enterprises in obtaining tax incentives, government subsidies, and industry access qualifications. On the other hand, the participation of state-owned shareholders sends positive signals to the external environment, helping to reduce information asymmetry between the funding providers and private enterprises. This encouragement facilitates external investors' entry and creates financing convenience for enterprises. In the eyes of many external investors, state ownership provides a reliable endorsement for the enterprise, indicating stronger operational capabilities and long-term development potential. For instance, state-owned capital can provide credit guarantees and help enterprises secure higher interest rate discounts. Therefore, state-owned capital infusion can alleviate the financing constraints on private enterprises, bringing in more external resources and thereby mitigating the resource constraints faced by private enterprises in the process of innovation. This, in turn, provides the necessary conditions for private enterprises to engage in high-quality green innovation.

Based on the analysis above, the following hypothesis is proposed in this study.

H4. State-owned capital participation can enhance the quality of green innovation in private enterprises by alleviating financing constraints.

3. Methodology

3.1. Variables and model specification

(1) Dependent Variable: Following the methods of N. Lahiri [12,41,53], the quality of green innovation (*GQuality*) is measured in this study by calculating the sum of the number of citations received by the green patents filed by the company in the following two years, as extracted from the CNRDS database. The sum is incremented by 1 and transformed using the natural logarithm.
(2) Independent Variable: The level of state-owned capital participation (*Share_S*) is used as the independent variable in this study. It is measured by the sum of the ownership percentage of state-owned shareholders among the top ten shareholders in private enterprises [43,72].
(3) Mediating Variables:

a) Environmental Consciousness: Environmental consciousness of the company is manifested through its environmental concepts and activities [82]. The stronger the company's environmental concepts and goals, and the more comprehensive its environmental management system, the greater the company's involvement in environmental activities, indicating a stronger environmental consciousness. Therefore, this study measures the strength of environmental consciousness. Based on whether the company discloses environmental concepts, establishes environmental goals, possesses an environmental management system, conducts environmental education and training, and participates in environmental special action assessments, a value of 1 is assigned if the company meets each of these indicators; otherwise, a value of 0 is assigned. The sum of these five indicators is used as the measure of environmental consciousness.

b) Related-party Transactions: related-party transactions are measured by the ratio of the sum of related-party transactions to total assets after excluding transaction categories that may contain noise. This serves as a proxy variable to measure the self-serving behavior of large shareholders.

c) Financing Constraints: This study adopts the research methodology of Fee et al. [8], using corporate financial indicators to construct a Logit model to measure the degree of financing constraints faced by companies. Specifically, first, three indicators, namely, company age (*Age*), cash dividend payout ratio (*CashDiv*), and firm size (*Size*), are standardized based on the year. After standardization, the sample companies are ranked based on the processed averages. The upper and lower tertiles are taken as the boundary points for financing constraints. A binary variable, *FC_Point*, is then set, with companies above the 66th percentile defined as the low financing constraints group ($FC\_Point = 0$), and those below the 33rd percentile defined as the high financing constraints group ($FC\_Point = 1$). Subsequently, utilizing model (1) for Logit regression, coefficients are obtained, and the probability $P(FC\_Point = 1)$ of encountering financing constraints each year is further derived as an indicator of financing constraints (*FC*). The range of *FC* is from 0 to 1, where a value closer to 1 indicates a higher degree of financing constraints for the company.

$$FC\_Point_{i,t} = \alpha_0 + \alpha_1 Scale_{i,t} + \alpha_2 Leverage_{i,t} + \alpha_3 \left(\frac{CashDiv}{TA}\right)_{i,t} + \alpha_4 MB_{i,t} + \alpha_5 \left(\frac{NWC}{TA}\right)_{i,t} + \alpha_6 \left(\frac{EBIT}{TA}\right)_{i,t} + \varepsilon_{i,t} \quad (1)$$

Where *Scale* represents the scale of the enterprise (natural logarithm of total assets), *Leverage* stands for the leverage ratio, *TA* denotes total assets, *Cashdiv* represents cash dividends, *MB* is the market-to-book ratio, *NWC* stands for net working capital, and *EBIT* signifies earnings before interest and taxes.

(4) Control Variables: company age (Age), company size (Size), return on assets (*ROA*), total debt ratio (*Leverage*), dual leadership structure (*Duality*), and R&D investment (*RD_Inv*) are selected as control variables in this study [52,83,84]. Additionally, fixed effects for industry and year are controlled. Please refer to Table 1 for the specific definitions of these variables.

(5) Model Specification: To examine the impact of state-owned capital participation on the quality of green innovation in private enterprises, this study constructs the following baseline regression model, as depicted in Equation (2).

$$GQuality_{i,t} = \alpha_0 + \beta_0 Share\_S_{i,t} + \gamma_0 Controls_{i,t} + \sum Industry + \sum Year + \varepsilon_{i,t} \quad (2)$$

Table 1
Definitions of variables.

Variable Category	Variable Symbol	Variable Name	Variable Definition
Dependent Variable	*GQuality*	Green Innovation Quality	The sum of the number of citations received by green patents filed by the company in the following two years, incremented by 1 and transformed using the natural logarithm.
Independent Variable	*Share_S*	State-Owned Shareholding Ratio	The sum of the ownership percentage of state-owned shareholders among the top ten shareholders.
Mediating Variable	*Awareness*	Environmental Awareness Indicator for environmental awareness of the company	Disclosure of environmental concepts: 1, 0. Establishment of environmental goals: 1, 0. Possession of environmental management system: 1, 0. Conducting environmental education and training: 1,0. Participation in environmental special action: 1, 0. The sum of these five indicators represents the measure of environmental awareness.
	Tunnel	Related-Party Transactions	The sum of related-party transactions divided by total assets.
	FC	Financing Constraints	Calculated based on the Logit regression model, the value ranges from 0 to 1. A value closer to 1 indicates a higher degree of financing constraints faced by the company. The specific calculation process is detailed in Equation (1).
Control Variable	*Age*	Company Age	The number of years since the establishment of the company plus 1.
	Size	Company Size	The natural logarithm of the total number of employees.
	ROA	Return on Assets	Net income divided by total assets.
	Leverage	Debt-to-Asset Ratio	Total debt divided by total assets.
	Duality	Dual Leadership Structure	Indicator for whether the Chairman and CEO positions are held by the same individual: 1, 0.
	RD_Inv	R&D Investment	R&D investment as a proportion of operating income.

Furthermore, to examine the mediating effects, this study adopts the testing procedure and establishes the following stepwise regression models.

a) Environmental Awareness. To test the mediating effect of environmental awareness, the following steps are taken, as illustrated in Equation (3) through (5).

$$Awareness_{i,t} = \alpha_0 + \beta_0 Share\_S_{i,t} + \gamma_0 Controls_{i,t} + \sum Industry + \sum Year + \varepsilon_{i,t} \tag{3}$$

$$GQuality_{i,t} = \alpha_0 + \beta_1 Awareness_{i,t} + \gamma_0 Controls_{i,t} + \sum Industry + \sum Year + \varepsilon_{i,t} \tag{4}$$

$$GQuality_{i,t} = \alpha_0 + \beta_0 Share\_S_{i,t} + \beta_1 Awareness_{i,t} + \gamma_0 Controls_{i,t} + \sum Industry + \sum Year + \varepsilon_{i,t} \tag{5}$$

b) Related-Party Transactions. To test the mediating effect of related-party transactions, the following steps are taken, as illustrated in Equation (6) through (8).

$$Tunnel_{i,t} = \alpha_0 + \beta_0 Share\_S_{i,t} + \gamma_0 Controls_{i,t} + \sum Industry + \sum Year + \varepsilon_{i,t} \tag{6}$$

$$GQuality_{i,t} = \alpha_0 + \beta_2 Tunnel_{i,t} + \gamma_0 Controls_{i,t} + \sum Industry + \sum Year + \varepsilon_{i,t} \tag{7}$$

$$GQuality_{i,t} = \alpha_0 + \beta_0 Share\_S_{i,t} + \beta_2 Tunnel_{i,t} + \gamma_0 Controls_{i,t} + \sum Industry + \sum Year + \varepsilon_{i,t} \tag{8}$$

c) Financing Constraints. To test the mediating effect of related-party transactions, the following steps are taken, as illustrated in Equation (9) through (11).

$$FC_{i,t} = \alpha_0 + \beta_0 Share\_S_{i,t} + \gamma_0 Controls_{i,t} + \sum Industry + \sum Year + \varepsilon_{i,t} \tag{9}$$

$$GQuality_{i,t} = \alpha_0 + \beta_3 FC_{i,t} + \gamma_0 Controls_{i,t} + \sum Industry + \sum Year + \varepsilon_{i,t} \tag{10}$$

$$GQuality_{i,t} = \alpha_0 + \beta_0 Share\_S_{i,t} + \beta_3 FC_{i,t} + \gamma_0 Controls_{i,t} + \sum Industry + \sum Year + \varepsilon_{i,t} \tag{11}$$

Among these, *Control* represents all control variables, while *Year* and *Industry* represent fixed effects for year and industry, respectively.

(6) Analytical Method

The dependent variable, the quality of green innovation (*GQuality*) and the mediating variables are all bounded variables (with values ≥ 0). Therefore, regression analysis is conducted using the Tobit model [85]. The regression results reported in the main analysis include the regression coefficients of the independent variables and the dependent variable for the respective time period.

3.2. Sample selection and data source

To investigate the impact of state-owned capital on the quality of green innovation in private enterprises, we selected A-share listed private companies in the Shanghai and Shenzhen stock markets from 2008 to 2020 (based on the nature of the actual controller) as the initial research sample. The research sample undergoes the following treatments. Exclusion of ST (Special Treatment) and financial private listed companies. Exclusion of companies with undetermined ownership nature or changes in ownership nature during the sample period. Exclusion of samples with missing variables. To mitigate the influence of outliers on empirical results, truncation at the 1% level is applied to related party transactions (*Tunnel*), return on assets (*ROA*), and total debt ratio (*Leverage*). After the screening process, the final dataset consists of 9734 observations from 1998 companies. The variable data utilized in this study are obtained from the following sources: The data relating to corporate green innovation are sourced from the China Research Data Services Platform (CNRDS) database, while other corporate data is sourced from The China Stock Market & Accounting Research (CSMAR) Database.

4. Results

4.1. Descriptive statistics

Firstly, the maximum value of green innovation quality (*GQuality*) during the sample period is 5.59. The average and median values are 0.203 and 0, respectively. This indicates a significant gap between the majority of private enterprises and those engaged in high-quality green innovation. While some private enterprises exhibit high-quality green innovation, the overall level of green innovation quality for most private enterprises remains relatively low. The maximum value of the state-owned shareholding ratio among the top

ten shareholders (*Share_S*) is 0.841, highlighting that state-owned capital has become an important component of the equity structure for certain private enterprises. The average and median values are 0.015 and 0, respectively, indicating that only a few private enterprises recognize the advantages of mixed-ownership reform and actively participate in it. The average value of environmental awareness (*Awareness*) is 0.643, which exhibits a significant gap from the maximum value. Additionally, the median value is 0, indicating that weak environmental awareness is a common issue faced by Chinese private enterprises. The median value of related-party transactions (*Tunnel*) is 0.093, suggesting that more than half of private enterprises engage in various degrees of related-party transactions. Table 2 presents the descriptive statistics of the main variables.

The correlation coefficients of the core variables are presented in Table 3. From the table, it can be observed that there is a positive correlation between the quality of green innovation and the proportion of state-owned shareholders, which is significant at the 1% level, supporting the hypothesized direction. The correlation coefficient between the quality of green innovation and environmental awareness is significantly positive, suggesting that environmental awareness can promote high-quality green innovation in private enterprises. The correlation coefficient between the proportion of state-owned shareholders and related-party transactions is significantly negative, indicating that the participation of state-owned shareholders effectively inhibits the opportunistic behavior of large shareholders in private enterprises. Based on the correlation coefficient between the proportion of state-owned shareholders and environmental awareness, it can be inferred that the involvement of state-owned shareholders strengthens the environmental awareness of private enterprises. Furthermore, in the regression analysis process, the Variance Inflation Factor (*VIF*) values of all variables were examined, and it was found that the *VIF* values for all variables were below 3. This indicates that the research findings are minimally affected by multicollinearity.

4.2. Regression results

Table 4 presents the regression results for the main effects and two mediating mechanisms. The first column (1) examines the influence of the proportion of state-owned shareholders on the quality of green innovation in private enterprises. It can be seen that the explanatory variable has a positive and significant impact on the quality of green innovation in private enterprises ($r = 2.874$, $p < 0.01$), supporting hypothesis 1. The inclusion of state-owned capital enhances the focus of private enterprises on environmental benefits, improves the internal governance environment of these enterprises, thereby stimulating their motivation for green innovation, and increases the significance placed on the quality of such innovation. Consequently, private enterprises become more actively involved in high-quality green innovation activities.

Columns (2) to (4) report the regression results of the mediating effect of environmental awareness in private enterprises. From column (2), it can be observed that there is a significant positive correlation between the proportion of state-owned shareholders ($r = 2.273$, $p < 0.01$) and environmental awareness. This implies that the integration of state-owned capital contributes to enhancing the environmental consciousness of private enterprises. The involvement of state-owned capital facilitates the government's transition from a distant stakeholder to a shareholder in private enterprises, thereby fostering a more proactive approach of private enterprises towards government accountability. Influenced by the dual objectives of the government, encompassing both economic and societal aspects, private enterprises increasingly prioritize social benefits, consequently bolstering their environmental awareness. Column (3) reports the regression results of the impact of environmental awareness on the quality of green innovation in private enterprises. There is a significant positive correlation between environmental awareness and the quality of green innovation in private enterprises ($r = 0.088$, $p < 0.01$), indicating that environmental awareness significantly enhances the quality of green innovation in private enterprises. This is because environmental awareness internally stimulates the subjective initiative of green innovation within private enterprises, leading them to no longer perceive green innovation solely as a "greenwashing" tool to merely comply with external environmental regulatory pressures. Consequently, driven by environmental consciousness, private enterprises will actively participate in responsible green innovation activities, thereby enhancing the quality of their green innovation efforts. Column (4) examines the mediating effect of environmental awareness between state ownership and the quality of green innovation. The regression coefficient for the proportion of state-owned shareholders is positive and significant, and the regression coefficient for environmental awareness is positive and significant. This indicates that the inclusion of state-owned capital enhances the environmental awareness of private enterprises, thereby improving the quality of their green innovation. Thus, hypothesis 2 is supported.

Table 2
The descriptive statistics of the main variables.

Variable	Number of Observations	Mean	Median	Standard Deviation	Min	Max	Interval
GQuality	9734	0.203	0.000	0.510	0.000	5.590	5.590
Share_S	9734	0.015	0.000	0.037	0.000	0.841	0.841
Awareness	9734	0.643	0.000	1.050	0.000	5.000	5.000
Tunnel	9734	0.189	0.093	0.256	0.000	1.380	1.380
FC	8220	0.595	0.639	0.241	0.000	0.987	0.987
Age	9734	16.500	16.000	5.570	2.000	63.000	61.000
Size	9734	7.460	7.390	1.030	4.230	12.400	8.200
ROA	9734	0.045	0.048	0.066	−0.302	0.198	0.500
Leverage	9734	0.359	0.347	0.173	0.055	0.788	0.733
Duality	9734	0.411	0.000	0.492	0.000	1.000	1.000
RD_Inv	9734	5.210	3.980	4.500	0.070	26.300	26.300

Table 3
The results of the correlation analysis of the main variables.

Variable	1	2	3	4	5	6	7	8	9	10	11
1.GQuality	1.000										
2.Share_S	0.043***	1.000									
3.Awareness	0.103***	0.052***	1.000								
4.Tunnel	−0.015	−0.039***	0.006	1.000							
5.FC	−0.225***	−0.103***	−0.246***	−0.067***	1.000						
6.Age	−0.018*	0.028***	0.053***	0.044***	−0.040***	1.000					
7.Size	0.219***	0.049***	0.263***	−0.026***	−0.649***	0.058***	1.000				
8.ROA	0.003	−0.004	0.071***	−0.204***	0.017	−0.054***	0.090***	1.000			
9.Leverage	0.144***	0.039***	0.098***	0.372***	−0.469***	0.065***	0.346***	−0.343***	1.000		
10.Duality	0.030***	−0.008	−0.057***	−0.017*	0.078***	−0.031***	−0.073***	0.020*	−0.052***	1.000	
11.RD_Inv	0.100***	0.011	−0.105***	−0.138***	0.138***	−0.005	−0.167***	−0.068***	−0.229***	0.080***	1.000

Note: ***, **, * indicate significance at 1%, 5%, and 10% levels, and the standard errors in brackets.

Table 4
The basic regression results.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	GQuality	*Awareness*	*GQuality*	*GQuality*	*Tunnel*	*GQuality*	*GQuality*	*FC*	*GQuality*	*GQuality*
Share_S	2.874***	2.273***		2.787***	−0.295***		2.781***	−0.479***		2.352***
	(0.646)	(0.687)		(0.645)	(0.065)		(0.645)	(0.052)		(0.723)
Awareness			0.088***	0.084***						
			(0.023)	(0.023)						
Tunnel						−0.360***	−0.340***			
						(0.111)	(0.111)			
FC									−1.142***	−1.086***
									(0.158)	(0.159)
Age	−0.005	0.015***	−0.005	−0.006	0.001	−0.004	−0.005	0.001***	−0.003	−0.004
	(0.005)	(0.005)	(0.005)	(0.005)	(0.000)	(0.005)	(0.005)	(0.000)	(0.006)	(0.006)
Size	0.464***	0.540***	0.442***	0.440***	−0.043***	0.452***	0.449***	−0.134***	0.307***	0.313***
	(0.027)	(0.028)	(0.028)	(0.028)	(0.003)	(0.028)	(0.028)	(0.002)	(0.035)	(0.035)
ROA	1.125***	2.723***	1.043**	1.038**	−0.237***	1.048**	1.041**	−0.049	1.060**	1.046**
	(0.433)	(0.463)	(0.433)	(0.433)	(0.040)	(0.434)	(0.433)	(0.030)	(0.445)	(0.445)
Leverage	1.849***	0.294	1.856***	1.835***	0.572***	2.069***	2.036***	−0.380***	1.338***	1.353***
	(0.182)	(0.187)	(0.182)	(0.182)	(0.017)	(0.192)	(0.192)	(0.013)	(0.203)	(0.203)
Duality	0.196***	−0.227***	0.200***	0.201***	−0.001	0.197***	0.198***	0.018***	0.241***	0.241***
	(0.051)	(0.053)	(0.051)	(0.051)	(0.005)	(0.051)	(0.051)	(0.004)	(0.054)	(0.054)
RD_Inv	0.090***	−0.031***	0.091***	0.090***	−0.004***	0.089***	0.088***	−0.001*	0.084***	0.083***
	(0.006)	(0.008)	(0.006)	(0.006)	(0.001)	(0.006)	(0.006)	(0.000)	(0.006)	(0.006)
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	−7.492***	−15.758	−7.170***	−7.284***	0.318***	−7.270***	−7.383***	1.535***	−4.954***	−5.186***
	(0.992)	(265.249)	(0.978)	(0.990)	(0.083)	(0.981)	(0.993)	(0.099)	(1.185)	(1.193)
Observations	9734	9734	9734	9734	9734	9734	9734	8220	8220	8220
Log *likelihood*	−5739.921	−10908.675	−5742.443	−5733.413	416.461	−5744.091	−5735.114	3090.111	−5044.627	−5039.463

Note: ***, **, * indicate significance at 1%, 5%, and 10% levels, and the standard errors in brackets.

Table 5
The robustness test (t-1 period independent variable).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	F.GQuality	*F.Awareness*	*F.GQuality*	*F.GQuality*	*F.Tunnel*	*F.GQuality*	*F.GQuality*	*F.FC*	*F.GQuality*	*F.GQuality*
Share_S	3.201***	3.243***		3.117***	−0.315***		3.092***	−0.465***		2.382***
	(0.777)	(0.817)		(0.776)	(0.081)		(0.777)	(0.059)		(0.791)
F.Awareness			0.072***	0.069***						
			(0.026)	(0.026)						
F.Tunnel						−0.367***	−0.345***			
						(0.123)	(0.123)			
F.FC									−1.267***	−1.218***
									(0.164)	(0.164)
Age	0.001	0.014**	0.001	0.000	0.001*	0.002	0.001	0.002***	0.003	0.002
	(0.006)	(0.006)	(0.006)	(0.006)	(0.001)	(0.006)	(0.006)	(0.000)	(0.006)	(0.006)
Size	0.407***	0.554***	0.386***	0.385***	−0.048***	0.391***	0.390***	−0.129***	0.237***	0.242***
	(0.031)	(0.032)	(0.032)	(0.032)	(0.003)	(0.031)	(0.031)	(0.002)	(0.037)	(0.037)
ROA	2.843***	3.771***	2.693***	2.727***	−0.334***	2.710***	2.742***	−0.442***	2.304***	2.339***
	(0.541)	(0.564)	(0.541)	(0.541)	(0.050)	(0.541)	(0.541)	(0.038)	(0.569)	(0.570)
Leverage	2.211***	0.501**	2.210***	2.194***	0.588***	2.441***	2.412***	−0.401***	1.661***	1.674***
	(0.207)	(0.210)	(0.207)	(0.206)	(0.020)	(0.219)	(0.219)	(0.015)	(0.220)	(0.220)
Duality	0.226***	−0.231***	0.228***	0.229***	−0.003	0.225***	0.227***	0.018***	0.245***	0.245***
	(0.057)	(0.060)	(0.057)	(0.057)	(0.006)	(0.057)	(0.057)	(0.004)	(0.057)	(0.057)
RD_Inv	0.096***	−0.032***	0.097***	0.096***	−0.004***	0.095***	0.094***	−0.001*	0.092***	0.092***
	(0.007)	(0.009)	(0.007)	(0.007)	(0.001)	(0.007)	(0.007)	(0.001)	(0.007)	(0.007)
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	−7.588***	−6.439***	−7.285***	−7.455***	0.344***	−7.305***	−7.475***	1.709***	−5.303***	−5.516***
	(1.037)	(1.093)	(1.027)	(1.039)	(0.096)	(1.026)	(1.039)	(0.069)	(1.047)	(1.058)
Observations	7282	7282	7282	7282	7282	7282	7282	7122	7122	7122
Log *likelihood*	−4478.652	−8532.395	−4482.885	−4475.073	169.358	−4482.320	−4474.646	2489.219	−4369.510	−4365.095

Note: ***, **, * indicate significance at 1%, 5%, and 10% levels, and the standard errors in brackets.

Columns (5) to (7) report the regression results of the mediating effect of controlling shareholder opportunistic behavior. From column (5), it can be observed that there is a significant negative correlation between the proportion of state-owned shareholders ($r = -0.295$, $p < 0.01$) and related-party transactions. This indicates that that the incorporation of state-owned capital can effectively mitigate the opportunistic behavior of controlling shareholders within private enterprises. The involvement of state-owned shareholders diversifies the internal equity structure of private enterprises and, backed by government support, effectively moderates the influence of controlling shareholders. This significantly enhances the internal governance environment of these enterprises, reinforces internal oversight, and effectively curbs the self-serving motives of controlling shareholders, thereby diminishing their capacity to extract resources from the company. The regression results in column (6) show that related-party transactions ($r = -0.360$, $p < 0.01$) significantly reduce the quality of green innovation in private enterprises. This phenomenon occurs because related-party transactions represent the primary avenue through which controlling shareholders divert resources from the company for their personal gain. On one hand, motivated by self-interest, controlling shareholders often opt for low-cost innovation models and engage in opportunistic behavior during the green innovation process to maximize personal benefits through resource extraction. This diminishes their motivation to pursue high-quality green innovation activities. On the other hand, the frequency of resource extraction activities by controlling shareholders reflects the extent of resource outflow from the company, thereby hindering the allocation of resources toward green innovation endeavors. Consequently, this results in a decline in the quality of green innovation. Column (7) examines the mediating effect of related-party transactions between state ownership and the quality of green innovation. The regression coefficient for the proportion of state-owned shareholders is positive and significant, while the regression coefficient for related-party transactions is negative and significant. This indicates that the inclusion of state-owned capital enhances the quality of green innovation in private enterprises by suppressing the opportunistic behavior of controlling shareholders. Therefore, Hypothesis 3 is validated.

Columns (8) to (10) report the relevant regression results for the mediating effect of financing constraints. In column (8), the results indicate a significant negative correlation between the proportion of state-owned shareholding ($r = -0.479$, $p < 0.01$) and financing constraints, suggesting that state-owned capital infusion effectively alleviates financing constraints in private enterprises. This phenomenon can be attributed to two main factors. Firstly, the participation of state-owned shareholders provides stable political connections for private enterprises, which helps alleviate policy discrimination during the resource allocation process. This, in turn, enhances private enterprises' ability to obtain external resources, thus alleviating resource pressures. Secondly, the involvement of state-owned capital sends a positive signal to the external environment, making private enterprises more attractive to external investors. This increased attractiveness facilitates access to investments from institutions such as banks, thereby further easing the financing difficulties faced by private enterprises. In column (9), the data indicate a significant negative impact of financing constraints ($r = -1.142$, $p < 0.01$) on the improvement of green innovation quality in private enterprises. This occurs because private enterprises, typically having limited internal resources, frequently rely on external support for their innovation endeavors. Green innovation demands significant and ongoing financial investment, with high-quality innovation entailing elevated research and development costs. However, lacking political affiliations, private enterprises often encounter financing bias, impeding their ability to secure external support. Consequently, this obstacle obstructs the sustained pursuit of high-quality green innovation activities. Column (10) investigates the mediating role of financing constraints in the relationship between state ownership and the quality of green innovation. The regression coefficient for the proportion of state-owned shareholding is positive and statistically significant, whereas the regression coefficient for financing constraints is negative and statistically significant. This suggests that the injection of state-owned capital, by alleviating financing constraints in private enterprises, improves the quality of green innovation. Therefore, empirical evidence supports Hypothesis 4.

4.3. Robustness test

To ensure the reliability of the research findings, this study conducts robustness checks in the following three aspects. Firstly, considering the possibility of lagged effects of the independent variables on the dependent variable, the dependent variable is lagged by one period before regression analysis. Table 5 reports the analysis results of the shareholding ratio of state-owned shareholders in period t and the green innovation quality of private enterprises in period t+1, as well as the analysis results of the intermediary effect between the shareholding ratio of state-owned shareholders in period t and the green innovation quality of private enterprises in period t+1. The results are basically consistent with Table 4.

Additionally, lagging the variables helps alleviate endogeneity issues caused by reverse causality between the explanatory and dependent variables. When state-owned shareholders choose investment targets, they are likely to select more promising enterprises. Higher quality of green innovation indicates stronger R&D capabilities of the firms. Therefore, private enterprises with higher green innovation quality may be more attractive to state-owned shareholders, leading to more inflows of state-owned capital. After implementing the lagged approach, the regression results remain largely unchanged, indicating that endogeneity issues are not severe.

Secondly, this study adopts a method inspired by J.P.H. Fan et al. [43], using the region where the sampled state-owned enterprises (SOEs) are located as a tool variable, indicating whether the region was forcibly opened as a concession or a trading port (Port) before the First Opium War until the establishment of New China. If the region was forcibly opened, Port equals 1 and zero otherwise. First, the regions that were forcibly opened have been significantly influenced by Western institutional culture, and their market systems are more developed. Therefore, private enterprises in these regions rely more on market resources for competition and have a lower likelihood of introducing state ownership, reducing their dependence on political connections [86]. Thus, presence of leased ports and territories in a region may influence the decision of private enterprises to introduce state capital. Second, the historical and cultural background of the region does not have an impact on the quality of green innovation in enterprises and the quality of green innovation in enterprises cannot have had any direct impact on their creation, since these concessions or trading ports were forcibly set by

foreigners over 100 years ago. To sum up, the instrumental variable meets the exogeneity criteria of instrumental variables and controls both potential reverse causality between state-owned capital between green innovation quality.

This study utilizes the ivtobit two-stage regression estimation to estimate the regression coefficients, and performs an endogeneity test using the weakiv command after regression, as shown in Table 6. Both the AR test and the Wald test reject the null hypothesis that the endogenous variable is unrelated to the instrument, indicating that the instrument is not weak. Moreover, the Cragg-Donald Wald F-statistic exceeds the critical value (16.38) significant at the 10% level for the weak instrument test, further confirming that the instrument is not weak. The Kleibergen-Paap rk LM statistic is significant at the 1% level, indicating that the instrument satisfies the homogeneity condition. The regression results of the first stage in Table 6 demonstrate a significant negative effect of the instrument variable on the proportion of state-owned shareholders, consistent with expectations. The regression results of the second stage show that even after controlling for possible endogeneity, the entry of state-owned capital still has a significant positive impact on the quality of green innovation in private enterprises, suggesting that the research findings are less affected by endogeneity interference.

Thirdly, to further alleviate the issues of reverse causality and omitted variables, this paper conducts a difference-in-differences (DID) test using the event of state-owned capital entering private enterprises as the research scenario. Drawing on established methodologies in existing literature [40], we conduct a DID test to assess the impact of this event on the variables of interest, as represented in Equation (12).

$$GQuality_{i,t} = \theta_0 + \theta_1 Treat_{i,t} \times Time_{i,t} + \theta_2 Treat_{i,t} + \theta_3 Controls_{i,t} + \sum Industry + \sum Year + \varepsilon_{i,t} \tag{12}$$

In this test, *Treat* represents a dummy variable indicating whether private enterprises receive state-owned capital. The treatment group consists of private enterprises with state-owned capital, where *Treat* is assigned a value of 1. The control group consists of enterprises that never introduced state-owned capital, and *Treat* is assigned a value of 0. *Time* is a time dummy variable indicating the year of state-owned capital entry into private enterprises. *Time* is assigned a value of 1 for the year and subsequent years of state-owned capital entry, and 0 otherwise. *Control* represents other control variables consistent with the main effect model.

Before conducting the difference-in-differences analysis, it is imperative to conduct a parallel trend test to ascertain whether this assumption holds within our sample. To verify this, we undertake an event study, referring to S.N. Nnamchi (2022) and C. Sun (2023) for guidance [87,88]. We employ Equation (13) to assess whether the treatment group and the control group exhibited disparate trends prior to the entry of state-owned capital into private enterprises, as well as to examine the dynamic impact of state-owned capital on the quality of green innovation.

$$GQuality_{i,t} = \theta_0 + \sum_{j=1}^{4} \theta_1^j Pre_{j,i,t} + \theta_2 Current_{i,t} + \sum_{k=1}^{5} \theta_3^k Post_{k,i,t} + +\theta_4 Controls_{i,t}$$

$$+ \sum Industry + \sum Year + \varepsilon_{i,t} \tag{13}$$

Firstly, dummy variables *time1* to *time4* are set, where *time1* is assigned a value of 1 for the year before state-owned capital entry into private enterprises, and 0 otherwise. Similarly, *time2* to *time4* are assigned values accordingly. These variables are then multiplied with *Treat* to form interaction terms *Pre1* to *Pre4*. Similarly, *time6* to *time10* are set as time dummy variables for the years after state-owned capital entry, multiplied with *Treat* to form interaction terms Post1 to Post5. $\theta_1^4 \sim \theta_1^1$ and $\theta_3^1 \sim \theta_3^5$ capture the difference of trends in the change of green innovation quality between the treatment group and the control group in each of the 4 pre-treatment years and 5 post-treatment years. Finally, a time dummy variable *time5* is set for the year of state-owned capital shareholding, forming an interaction term *Current* with *Treat*. θ_2 measures the immediate effect of the state-owned capital on quality of green innovation during the implementation year. Regression is performed on the dependent variable and the interaction terms, as shown in Column (1) of Table 7.

The regression coefficients for *Pre1* to *Pre4* are not statistically significant, suggesting that there is no evidence indicating that other potential factors influence the change in parallel trends between the treatment group and the control group. However, the coefficients

Table 6
The instrumental variable method to test endogeneity.

	First Stage	Second Stage
Variable	*Share_S*	*GQuality*
Port	−0.005*** (0.001)	–
Share_S	–	28.125* (15.066)
Control variables	Yes	Yes
Year & industry	Yes	Yes
Observations	9734	
Adjust-R²	0.021	–
Instrumental variable *F* statistics	6.71***	–
AR	4.000**	
Wald	3.480*	
Kleibergen-Paap rk LM	21.798***	
Cragg-Donald Wald F	21.764	

Note: ***, **, * indicate significance at 1%, 5%, and 10% levels, and the standard errors in brackets.

Table 7
The green innovation robustness test results.

	(1)	(2)
	GQuality	*GQuality*
Pre4	−0.042	
	(0.203)	
Pre3	−0.058	
	(0.157)	
Pre2	0.126	
	(0.132)	
Pre1	−0.056	
	(0.120)	
Current	0.149	
	(0.091)	
Post1	0.268***	
	(0.096)	
Post2	0.215**	
	(0.101)	
Post3	0.234**	
	(0.106)	
Post4	0.365***	
	(0.109)	
Post5	0.349***	
	(0.082)	
Treat×Time		0.271***
		(0.074)
Treat		−0.017
		(0.087)
Control	Yes	Yes
Year	Yes	Yes
Industry	Yes	Yes
Constant	−7.214***	−7.313***
	(0.982)	(0.988)
Observations	9734	9734
Log *likelihood*	−5733.642	−5737.153

Note: ***, **, * indicate significance at 1%, 5%, and 10% levels, and the standard errors in brackets.

for *Post1* to *Post5* are significant, indicating that the entry of state-owned capital plays a crucial role in enhancing the quality of green innovation in private enterprises. The lack of significance for the Current coefficient may be attributed to a delayed effect of the state-owned capital entry. Consequently, the test results fulfill the basic requirements of the difference-in-differences test. The enhancement of green innovation quality in private enterprises is less likely to be attributable to factors other than the entry of state-owned capital. Column (2) of Table 7 reports the regression results of the difference-in-differences model. The coefficient of *Treat* × *Time* ($r = 0.271$, $p < 0.001$) is positive and significant, indicating that the entry of state-owned capital into private enterprises indeed improves the quality of green innovation to some extent, mitigating potential endogeneity issues in this research.

This study examines whether the entry of state-owned capital can enhance the green innovation quality of private enterprises.

Table 8
The Heckman two-stage regression results.

	(1)	(2)
	IsGreen	*GQuality*
Share_S		2.354***
		(0.674)
City_EN	−0.041***	
	(0.013)	
IMR		1.250***
		(0.443)
Control	Yes	Yes
Year	Yes	Yes
Industry	Yes	Yes
Constant	−2.533***	−7.209***
	(0.502)	(1.386)
Observations	8453	4515
Log *likelihood*	−5203.834	−4096.044

Note: ***, **, * indicate significance at 1%, 5%, and 10% levels, and the standard errors in brackets.

However, it is possible that some private enterprises, despite receiving state-owned capital, may not necessarily engage in green innovation. This portion of the sample may introduce sample self-selection issues to the research. To mitigate this endogeneity problem, it is necessary to first predict the likelihood of a private enterprise engaging in green innovation and then examine the impact of state-owned capital on the green innovation quality using the sample of private enterprises that conduct green innovation. Therefore, this paper employs the Heckman two-step method to test the existing research model. Specifically, appropriate instrumental variables are selected to estimate a Probit model for the first-stage regression, predicting whether a private enterprise engages in green innovation activities (*IsGreen*). The inverse Mills ratio (*IMR*) is calculated and included as a control variable in Model (2) to test the main effect. Considering that the higher the environmental governance level in the location of private enterprises, the more likely they are to enhance their legitimacy in the local market through green innovation, the environmental level of the enterprise's location may affect its decision on green innovation. However, due to information asymmetry, external stakeholders cannot accurately evaluate the quality of green innovation, resulting in minimal legitimacy benefits for green innovation. Therefore, the city's environmental conditions where the enterprise is located are unlikely to affect the green innovation quality, satisfying the requirements of relevance and excludability. The natural logarithm of industrial sulfur dioxide emissions in the city where the enterprise is located (*City_EN*) is used as the instrumental variable. Table 8 reports the regression results of the Heckman two-step test.

Column (1) shows that the coefficient of the exogenous variable *City_EN* is −0.041 ($p < 0.01$), indicating that as the local environmental conditions worsen, private enterprises are less inclined to seek legitimacy through green activities, resulting in a lower likelihood of engaging in green innovation. From the regression results in Column (2), it can be observed that the IMR coefficients in the models related to green innovation quality are all significant at the 1% level, indicating the presence of sample self-selection issues in the research sample. After including the IMR as a control variable in the model, the main effect and mediating effect remain significant, suggesting that the research results remain robust even after controlling for self-selection bias.

To distinguish the specific effect of state-owned capital, the authors have undertaken a rigorous analysis in this paper. Notably, the sample excludes companies involved in ESG ratings, and the primary effect is examined. Even after accounting for the external factor of ESG ratings, the regression results for the primary effect remain statistically significant (See Table 9). This suggests that the empirical findings maintain robustness, demonstrating the resilience of the original results when considering the influence of ESG ratings as an alternative explanation.

4.4. Heterogeneous test

Based on the preceding analysis, it can be observed that state-owned capital infusion primarily enhances the environmental responsibility of enterprises, improves internal governance environments, alleviates financing constraints, and consequently enhances the green innovation quality of private enterprises. However, the role of diversified equity structure as an internal governance mechanism in influencing the green innovation quality of private enterprises may be subject to the impact of the external governance environment. Therefore, this paper, based on the perspectives of social supervision and institutional supervision, further explores the boundary conditions of state-owned capital infusion in improving the green innovation quality of private enterprises.

Table 9
The main effect test results (excluding ESG rated companies).

	(1)
	GQuality
Share_S	3.937***
	(0.750)
Age	−0.002
	(0.006)
Size	0.367***
	(0.038)
ROA	1.299**
	(0.526)
Leverage	1.516***
	(0.211)
Duality	0.180***
	(0.060)
RD_Inv	0.098***
	(0.008)
Year	Yes
Industry	Yes
Constant	−6.462***
	(1.112)
Observations	7707
Log *likelihood*	−4070.494

Note: ***, **, * indicate significance at 1%, 5%, and 10% levels, and the standard errors in brackets.

4.4.1. Social supervision

With the increasing national emphasis on environmental issues, a company's green transformation and environmental compliance have become crucial indicators for assessing its legitimacy. The media, as an effective social supervisory mechanism, not only amplifies the positive signals conveyed by green transformation, enhancing the legitimacy of enterprises, but also magnifies the negative impact of environmental violations, reducing the legitimacy of companies [12,89]. Therefore, under heightened media attention, private enterprises are bound to be more concerned about the impact of environmental responsibility. State-owned shareholders are more likely to enhance the environmental responsibility of enterprises under intense media scrutiny, internally boosting the subjective initiative of enterprises for green innovation and encouraging them to engage in high-quality green innovation. This paper uses the natural logarithm of the sum of annual news reports related to listed companies plus 1 as a measure of media attention (Media). By setting the interaction term between media attention and independent variables, this study examines its impact on the relationship between state-owned capital and the green innovation quality of private enterprises, as shown in Table 10. The data indicates that companies with higher media attention, state-owned capital infusion is more effective in improving the green innovation quality of private enterprises.

4.4.2. Institutional supervision

Compared to the media's reporting on corporate behavior, auditors can convey more reliable information to stakeholders based on their professional competence [12], reducing information asymmetry between enterprises and stakeholders. This study uses the audit firm to which auditors belong as a grouping condition to examine the impact of external institutional supervision on the relationship between state-owned capital and the green innovation quality of private enterprises, as shown in Table 10. The data shows that the higher the level of the audit firm providing audit services to a company, the weaker the role of state-owned capital infusion in improving the green innovation quality of private enterprises. This is because external audits can effectively enhance the quality of financial information, acting as a substitute for internal governance. On one hand, it can reduce internal information asymmetry and effectively curb opportunistic behavior by controlling major shareholders. On the other hand, it can disclose reliable accounting information to the external market, reducing information asymmetry between enterprises and external stakeholders, strengthening external supervision of enterprises, and further suppressing opportunistic behavior by major shareholders. Existing research indicates that compared to other small and medium-sized firms, auditors from the "Big Four" accounting firms can provide higher quality audit services to enterprises, and they have a stronger substitutive effect on internal governance mechanisms, leading to a weakened mechanism through which state-owned capital improves the green innovation quality of private enterprises through internal governance effects.

5. Discussion and conclusion

Improving the quality of green innovation for enterprises undoubtedly plays a crucial role in promoting the high-quality development of private enterprises and realizing the national green development strategy. This study selects privately listed companies on the A-share markets of Shanghai and Shenzhen from 2008 to 2020 as the research subjects. The research reveals the following findings: (1) The entry of state-owned capital can stimulate the internal motivation for green innovation in private enterprises, improve their internal governance, and subsequently enhance the quality of their green innovation. (2) Mechanism analysis indicates that, state-owned capital strengthens the environmental awareness of private enterprises, stimulates their intrinsic motivation for green innovation, weakens their "greenwashing" behavior, and promotes high-quality green innovation. State-owned capital curbs opportunistic behavior by the major shareholders of private enterprises, reduces their motivation for arbitrage during the green innovation process, and improves the quality of green innovation. The signaling effect generated by state-owned capital investment can effectively

Table 10
Heterogeneity test of external governance environment.

	Media attention	Audit firm	
		The four leading firms	Other
	GQuality	*GQuality*	*GQuality*
Share_S	−1.914	8.608	2.811***
	(2.278)	(6.332)	(0.645)
Share_S×Media	1.429**		
	(0.644)		
Media	0.132***		
	(0.036)		
Control	Yes	Yes	Yes
Year	Yes	Yes	Yes
Industry	Yes	Yes	Yes
Constant	−5.554***	−9.823***	−9.777***
	(0.620)	(0.787)	(0.803)
Observations	9734	279	9455
Log *likelihood*	−5727.285	−173.994	−5540.102

Note: ***, **, * indicate significance at 1%, 5%, and 10% levels, and the standard errors in brackets.

alleviate the financing constraints faced by private enterprises, thereby reducing the resource pressure on enterprises in the R&D process, allowing enterprises to invest more resources in innovation activities and carry out high-quality green innovation. (3) Heterogeneity analysis reveals that the impact of state-owned capital on the quality of green innovation in private enterprises varies across different external supervisory environments. After conducting a series of robustness tests, the above research conclusions remain unchanged.

This study discovers that private enterprises enhance their internal motivation for green innovation, improve their internal governance environment, and alleviate resource pressure by introducing state-owned capital, thereby enhancing the quality of their green innovation. Firstly, state-owned capital entry enables a role transition for the government from a distant stakeholder to a shareholder of the enterprise. Its social objectives can internally reinforce the environmental awareness of private enterprises, thereby stimulating their internal motivation for green innovation and improving the quality of green innovation. Secondly, the participation of state shareholders can elevate the internal monitoring level of private enterprises, restrain the opportunistic motives of large shareholders in private enterprises during the green innovation process, and enhance the quality of green innovation. Heterogeneity analysis demonstrates that the promotion effect of state-owned capital entry on the quality of green innovation in private enterprises is more significant in companies with higher media attention and lower audit quality.

The theoretical contributions and practical significance of this study are primarily manifested in the following aspects:

Firstly, this paper examines the impact of "reverse mixed-ownership reform" on the green innovation activities of private enterprises by integrating with China's vigorous promotion of mixed-ownership reform. On the one hand, it enriches the related research on the influence of mixed-ownership reform on private enterprises [90]. On the other hand, it expands the academic achievements regarding the determinants of green innovation quality in enterprises. Existing studies have extensively explored the factors influencing green innovation in enterprises [41,44,45,91], but they have paid limited attention to green innovation quality, focusing only on factors such as environmental regulations and corporate transformation and upgrading. In contrast, this paper further explores the determinants of green innovation quality in enterprises from the perspective of corporate ownership structure.

Secondly, this paper reveals in-depth the mechanism through which state-owned capital affects the green innovation quality of private enterprises, thereby further enriching the research on the economic consequences of changes in ownership structure and the determinants of green innovation quality in enterprises. Moreover, it sheds light on the boundary conditions of the influence of state-owned capital on the green innovation quality of private enterprises from an external governance perspective.

Thirdly, the conclusions of this paper indicate that the entry of state-owned shareholders can stimulate the green innovation drive and enhance the green innovation capacity of private enterprises, thereby improving the green innovation quality. From the perspective of "reverse mixed-ownership reform," this study contributes to the existing research on corporate reform. The evaluation of the effects of private enterprises' participation in mixed-ownership reform is currently diverse. This paper further explores the effects of mixed-ownership reform in private enterprises from the perspective of green innovation quality.

6. Limitations and future research

This study explores how to leverage national power to stimulate the motivation for green innovation in private enterprises and improve the quality of green innovation. It provides important insights for the high-quality development of private enterprises and government policies. From a policy perspective, this research demonstrates that the entry of state-owned capital contributes to enhancing the quality of green innovation in private enterprises. Therefore, the Chinese government should steadfastly deepen the mixed-ownership reform, encourage more private enterprises to participate, and, in the new round of mixed-ownership reform, provide state-owned capital injections to privately-owned companies with lower green innovation quality to improve their green innovation. Additionally, the government should further improve the external governance mechanisms of enterprises, strengthen and complement the governance effects of state-owned capital within private enterprises through external supervision mechanisms, and support the high-quality development of private enterprises.

From an enterprise perspective, low-quality green innovation is detrimental to long-term development. If private enterprises want to achieve true high-quality development and enhance their competitiveness, they must reform and enhance their innovation capabilities. Therefore, private enterprises should fully recognize the resource and governance advantages of state-owned capital and actively participate in the process of mixed-ownership reform, leveraging national power to achieve high-quality development. Firstly, private enterprises can form a diversified ownership structure by participating in the mixed-ownership reform, establish more diversified business objectives, and avoid neglecting environmental issues due to excessive pursuit of economic benefits. This internal stimulation enhances the environmental responsibility of private enterprises and improves their motivation for green innovation, thereby addressing the problem of insufficient green innovation caused by a lack of motivation. Secondly, private enterprises can optimize their internal governance mechanisms by altering the ownership structure, effectively curbing opportunistic behavior by major shareholders during the research and development process, and improving the decline in green innovation quality caused by internal governance issues. Finally, the promotion effect of state-owned capital on the quality of green innovation in private enterprises varies significantly across different external supervisory environments. Therefore, private enterprises seeking to enhance their green innovation level through state-owned capital should develop suitable reform plans based on the external governance environment, ultimately achieving high-level green development.

This paper primarily examines the mediating effects of environmental consciousness and controlling shareholder opportunistic behavior in the relationship between state-owned capital and green innovation quality in private enterprises. Future research can explore other pathways through which state-owned capital affects green innovation quality in private enterprises in the context of mixed-ownership reform. This study focuses on private enterprises and specifically addresses green innovation quality. However, as

state-owned enterprises are the main entities in China's mixed-ownership reform, it is worth investigating whether their green innovation behavior is also influenced by mixed-ownership reform. Future research can select state-owned enterprises as research samples and simultaneously examine the quantity and quality dimensions of green innovation, exploring the impact of mixed-ownership reform on the green innovation activities of state-owned enterprises, thus further testing and expanding the theoretical framework of this study.

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Data availability statement

The primary Data generated or analyzed during this study are available from the China Stock Market & Accounting Research (CSMAR) database (https://www.gtarsc.com) and Chinese Research Data Services Platform (CNRDS) database (https://www.cnrds.com), which requires purchase for access. The authors do not have the right to freely distribute or share the data obtained from the CSMAR and CNRDS, and users must comply with the terms and conditions of the database. The data associated with our study was not deposited into a publicly available repository.

CRediT authorship contribution statement

Haifeng Yan: Writing – review & editing, Methodology, Investigation, Conceptualization. **Zhengyi Chen:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yunpeng Yang:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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