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How do controlling shareholder pledges affect corporate green innovation: Evidence from China

Authors:
Lifu Liu[1]
Pengzhen Liu[1,2]

Affiliations:
[1]School of Economics, Jinan University, Guangzhou, China

[2]College of Business, Quzhou University, Quzhou, China

Corresponding author:
Pengzhen Liu,
liupengzhen@stu2022.jnu.edu.cn

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Background: Green innovation is essential for sustainable development but often faces financial and managerial constraints in emerging markets. Controlling shareholders' behaviours, such as equity pledges, may impact firms' long-term innovation incentives.

Aim: This study investigated how controlling shareholders' equity pledges influence corporate green innovation and explores the underlying mechanisms and contextual variations of this relationship.

Setting: The research focused on Chinese A-share listed companies over the period from 2012 to 2022, offering insights from an emerging market context where both green transformation and equity pledging practices are prevalent.

Method: Using panel data regression analysis and mediation models, the study examines the direct impact of equity pledges on green innovation, and further analyses three mediating channels: Environmental, Social and Governance (ESG) performance, financing constraints, and tunnelling behaviour.

Results: The results show that controlling shareholders' equity pledges significantly reduce firms' green innovation efforts, primarily by lowering research and development (R&D) investment. The adverse effects operate through worsened ESG performance, tighter financing constraints, and increased tunnelling activities. However, the inhibitory effect is mitigated in firms with low pledge ratios, high pollution levels, or state ownership.

Conclusion: Equity pledging by controlling shareholders poses a substantial threat to green innovation in most firms, although certain firm characteristics can buffer this effect.

Contribution: This article contributes to the literature by uncovering the dark side of shareholder pledging behaviour in the context of environmental innovation, highlighting the need for regulatory scrutiny and corporate governance reforms to safeguard long-term sustainable development.

Keywords: equity pledge; green innovation; ESG performance; financing constraint; tunnelling.

Introduction

Corporate green innovation

Over the past century, human society has achieved significant advancements in science, technology, and economics. However, these developments have adversely impacted the environment, despite improvements in social productivity (Nawaz et al. 2021). The ongoing deterioration of environmental conditions has resulted in increased occurrences of extreme weather, soil erosion, resource depletion, and desertification, all of which severely affect regional ecosystems. Consequently, finding a balance between economic growth and sustainable development has emerged as a critical challenge for countries worldwide (Guo, Zhao & Fu 2025).

Neoclassical economics posits that environmental protection policies impose an increased production burden on enterprises, thereby raising their production costs and negatively impacting economic growth (Opschoor 1997). However, this perspective primarily focuses on the cost implications of environmental protection, neglecting the potential benefits of technological advancements driven by corporate innovation that can enhance productivity (Illge & Schwarze 2009). Porter's hypothesis introduces the role of corporate innovation into the relationship between environmental protection and economic growth (Porter & Van der Linde 1995). While it is true that the responsibility for environmental protection can elevate production costs in the short term, it can also incentivise companies to pursue technological innovation. This, in turn,

improves productivity and competitiveness, leading to positive long-term effects on economic growth (Matemane, Msomi & Ngundu 2024; Peng & Kong 2024). Green innovation refers to the use of technological or non-technological innovative methods by enterprises to reduce the environmental impact during the production process, while simultaneously improving resource utilisation efficiency and reducing resource waste caused by inefficient production. Moreover, scholars have recognised the significance of green innovation for both environmental sustainability and economic development (Li et al. 2024). Corporate green innovation emerges as a crucial strategy for achieving the dual objectives of economic growth and environmental protection simultaneously.

Controlling shareholder equity pledges

Equity pledge is a method in which shareholders of listed companies pledge their own shares to financial institutions in exchange for financing, essentially a form of collateralised loan. However, unlike general asset-based financing, equity pledge involves issues related to corporate control and stock price volatility, especially when controlling shareholders are involved (Dou, Masulis & Zein 2019; Guo, Ke & Tang 2023).

Equity, as a form of ownership, possesses unique characteristics when used as collateral for financing. On the one hand, equity is not a direct component of an enterprise's daily operations. By pledging ownership stakes in listed companies, equity pledges transform static assets into potential drivers of corporate growth (Pang & Wang 2020). On the other hand, unlike direct stock reductions, equity pledges do not immediately exert downward pressure on stock prices (Wang & Zhang 2024). In addition, the procedures and approvals for equity pledging are generally simpler and more convenient, which can broaden financing avenues for companies and help alleviate capital constraints (Bhatia et al. 2019). However, it is important to note that equity pledging fundamentally constitutes a form of collateral financing. When a company's performance deteriorates and its share price declines, there is a potential risk of control transfer if controlling shareholders engage in equity pledging (Chen & Hu 2024).

Because of the risk of control transfer, controlling shareholders may adjust their risk appetite following equity pledges. As the majority shareholder typically holds the most voting rights, their risk tolerance significantly influences the enterprise's operations and decision-making processes (Li et al. 2025; Pang & Wang 2020). Investing in green innovation requires substantial resources, both tangible and intangible, and these initiatives often involve long timelines from input to output. Such investments can negatively impact short-term performance, putting downward pressure on share prices and increasing the risk of equity unwinding (Dou et al. 2019). To safeguard their control from unwinding, controlling shareholders may implement conservative operating policies after making equity pledges, aiming to minimise short-term stock price volatility (Guo et al. 2023). Consequently, they may reduce long-term investments, including research and development (R&D) expenditures, to mitigate short-term business risks. This effect tends to be more pronounced when the proportion of controlling shareholders' equity pledges is higher (Pang & Wang 2020).

Institutional background and literature review

As a representative of emerging economies globally, China has made significant contributions to green and sustainable development (Tan, Liu & Cheng 2024). Promoting corporate green innovation is an effective measure to balance economic growth with environmental protection. In addressing environmental issues, China has pushed for sustainable corporate practices at the micro level through policy guidance, the issuance of green bonds, encouragement of green finance, and the formulation of environmental regulations (Xia et al. 2022; Zhang, Mohsin & Taghizadeh-Hesary 2022; Zhang et al. 2024a). On the one hand, the government has injected financial momentum into corporate green transformation by establishing green industry funds, issuing green bonds, and providing green subsidies. These initiatives enable businesses to access more green capital for innovation investments, thereby increasing the output of green innovation patents (Praveen, Rath & Akram 2025; Zhang et al. 2022). On the other hand, the Chinese government has enacted laws and regulations to punish and regulate companies that exceed pollution standards. Key legal frameworks, such as the Measures for Ecological and Environmental Administrative Punishments, the Regulations on the Levy and Use of Pollutant Emission Charges, the Environmental Protection Tax Law of the People's Republic of China, and the Ecological Protection Compensation Regulations, impose environmental taxes on high-polluting enterprises and strictly punish those who damage the ecosystem during production. These legislative measures encourage polluting companies to adopt green innovation technologies, reduce pollution emissions in the production process, improve resource utilisation efficiency, and stimulate the internal motivation for green innovation (Zhang et al. 2025).

A substantial body of research has demonstrated the impact of external regulatory forces on corporate green innovation. Government incentives and regulatory oversight are critical factors influencing green innovation (Zhang et al. 2024a). Government agencies can stimulate this innovation by enhancing environmental legislation (Brunnermeier & Cohen 2003; Peng & Kong 2024), imposing environmental protection taxes on businesses (Wang & Yu 2021), and implementing stringent controls on carbon emissions, thereby encouraging enterprises to pursue green transformation. Furthermore, government green subsidies serve as an effective means of promoting green innovation (Han et al. 2024). By providing direct financial support, these subsidies help to alleviate the R&D burden on companies and increase their motivation for engaging in green initiatives (Xia et al. 2022). Furthermore, the government can facilitate green innovation through the establishment of green funds (Chi et al. 2023), encouraging banks to increase green credit (Benfratello, Schiantarelli & Sembenelli 2008), assisting businesses in issuing green bonds

(Dong, Zhang & Zheng 2024), and advancing green finance initiatives (Behera, Behera & Sethi 2024). Internal governance also plays a significant role in influencing corporate green innovation.

A growing body of literature analyses the relationship between internal corporate characteristics and corporate green innovation. Ji, Suo and Yu (2025) found that a culture of opportunism can lead to internal resource misallocation, thus suppressing the willingness of companies to invest in green innovation. The involvement of green investors can incentivise companies to prioritise environmental and ecological considerations, thereby fostering corporate green transformation and innovation (Tang, Tong & Chen 2024). Furthermore, enterprise ESG (Environmental, Social, and Governance) performance is strongly correlated with green innovation. On the one hand, ESG performance has a positive impact on financial performance (Matemane et al. 2024). High-performing companies tend to have better resource allocation structures and stronger innovation incentives (Manso 2011). On the other hand, companies that exhibit higher ESG performance demonstrate a stronger sense of environmental responsibility, making it easier for them to attract green funds, which improves their green financing level and helps secure more financial support for green innovation (Peng & Kong 2024; Zhang, Zhao & Meng 2024b). Moreover, companies that actively engage in digital transformation also positively impact green innovation. The use of digital technologies such as big data and artificial intelligence can effectively reduce costs and increase profits (Rong & Liu 2024), thus improving resource allocation efficiency and driving the development of green innovation (Tao et al. 2024).

Existing literature predominantly focuses on the impact of controlling shareholders' equity pledges on internal controls and financial decision-making. For example, equity pledging by controlling shareholders often leads to decision-making that favours short-term speculation over long-term development (Dou et al. 2019; Guo et al. 2023). Companies may reduce their willingness to invest in R&D and other long-term investments (Pang & Wang 2020). Equity pledging can lead to behaviours that harm the interests of other shareholders, such as fund misappropriation (Zhao et al. 2024), real earnings management (Bhatia et al. 2019), related-party transactions (Liu & Tian 2012), and profit manipulation (Pan & Qian 2023).

Green innovation is characterised by long investment cycles, significant capital requirements, and high risks (Ji et al. 2025; Peng & Kong 2024). Equity pledging, however, tends to trigger speculative strategies focused on risk avoidance and short-term performance (Guo et al. 2023). We observe that the proportion of equity pledging by controlling shareholders in China's capital markets has been rising annually and has become a common financing tool (Chan et al. 2018; Fan & Wong 2002). The increasingly high levels of pledging have reached a point where their impact on green innovation can no longer be ignored. Therefore, understanding the effect of equity pledging by controlling shareholders on green innovation is an important research topic within the context of China's green development strategy. This article uses China's experience to focus on the impact of controlling shareholders' equity pledges on green innovation, identifying the inhibitory effect that exists. This finding has practical significance for emerging economies, such as China, in promoting corporate green innovation.

Research contributions

Existing studies have yet to fully explain the relationship between controlling shareholders' equity pledges and corporate green innovation. As green innovation is a crucial component of global sustainable development, this article fills the gap by examining the impact of equity pledging on green innovation within the context of China, an important emerging market. This article analyses data from A-share listed companies spanning from 2012 to 2022 to investigate the effects of equity pledges on corporate green innovation and the underlying mechanisms involved. The contributions of this research to the field of green innovation are twofold. Firstly, this study provides empirical evidence regarding the impact of controlling shareholders equity pledge on corporate green innovation, highlighting the negative effects of their pledging behaviours. Pledges by controlling shareholders can lead to short-term thinking within enterprises, prompting them to prioritise immediate high-yield projects. This behaviour can crowd out long-term investments and R&D efforts, ultimately diminishing the innovation capacity of these firms. Secondly, the article elucidates the mechanisms through which controlling shareholders' equity pledges influence corporate green innovation. Equity pledges tend to compress corporate ESG investments, resulting in poorer ESG performance. A decline in ESG scores can deter external green investors, complicating efforts to secure adequate resources for green innovation projects. Furthermore, equity pledges negatively impact corporate financing, exacerbating financial constraints and making it challenging for firms to obtain sufficient funds for R&D investments, which subsequently reduces their green innovation output. Moreover, controlling shareholders' equity pledges increases the separation between cash flow rights and control rights, heightening the risk of misappropriation of corporate funds and leading to insufficient R&D expenditures, thereby weakening green innovation capacity. Finally, this article considers the heterogeneity of firms in relation to green innovation, examining how the proportion of controlling shareholders' pledges, the degree of pollution in their industries, and the presence of state-owned equity can differentially affect these dynamics.

Theoretical hypothesis

Analysis of controlling shareholders' equity pledge behaviour

Control transfer risk is a significant concern associated with controlling shareholders' equity pledges (Pang & Wang

2020). In the context of Chinese enterprises, the limited separation of powers often places controlling shareholders in a dominant position within corporate governance. This dominance can enable them to pursue personal interests, potentially at the expense of broader corporate objectives (Jiang, Lee & Yue 2010; Fan & Wong 2002). While some scholars argue that equity pledges can help alleviate corporate financing constraints by broadening funding channels (Pang & Wang 2020), it is essential to recognise that these pledges may simultaneously heighten controlling shareholders' focus on their private interests.

During the period of an equity pledge, controlling shareholders are likely to prioritise the security of their investments, becoming increasingly cautious to avoid control loss that could result from a decline in share prices (Chan et al. 2018). This protective stance may lead them to adjust business strategies in ways that emphasise stability over growth. Specifically, they might choose to support steady operational practices, reducing investments in high-risk projects that require substantial capital and long timelines. Instead, they may favour projects that promise quick returns, prioritising short-term financial gains over long-term innovation (Chan et al. 2018; Hu et al. 2021).

However, the risk of control transfer does not completely restrain the behaviour of controlling shareholders (Liu & Tian 2012; Wang & Zhang 2024). These individuals retain significant power over enterprise resources and can manipulate corporate capital to their advantage. Even after pledging equity for funding, controlling shareholders typically maintain control of the enterprise. When their interest in controlling the enterprise outweighs the benefits of cash flow for the company, they may exploit their control rights to misappropriate corporate funds (Liu & Tian 2012). Such behaviour can ultimately undermine the firm's capacity for green innovation, as resources that could have been directed towards innovative projects may instead be diverted to fulfil the personal interests of shareholders.

Characteristics of green innovation

Green innovation projects, by their nature, typically necessitate longer time cycles and substantial capital investments (Degirmenci et al. 2024). These projects inherently involve significant uncertainty for enterprises (Chi et al. 2023). Short-term investments in green innovation may not yield favourable returns, and the development of green innovation capabilities requires sustained investment over time to achieve meaningful results (Chi et al. 2023; Ji et al. 2025). Furthermore, the benefits derived from green innovation initiatives – such as obtaining patents – can take years to materialise. Many patents may initially serve merely as technological reserves until a viable market develops (Degirmenci et al. 2024).

The uncertainty surrounding green innovation is compounded by the characteristics of technological iteration. Particularly during competitive market phases, companies may not have established effective technical barriers to protect their innovations (Degirmenci et al. 2024). This situation exposes green innovation patents to the risk of obsolescence because of competitive advancements, making it crucial for firms to remain agile and continuously invest in their innovations (Chi et al. 2023). Moreover, green innovation differs from conventional corporate innovation in that the reputational incentives for enterprises and managers often outweigh direct financial benefits (Tang et al. 2024). When companies recognise the importance of social responsibility and environmental protection, they are more likely to enhance their incentive systems for green innovation and R&D personnel. Such recognition fosters an environment conducive to innovation, encouraging employees to pursue projects that contribute to sustainability and environmental stewardship (Dong et al. 2024).

The impact of controlling shareholders' equity pledge on green innovation decision-making

The effects of controlling shareholders' equity pledges, such as exacerbated agency problems, increased tunnelling incentives, and heightened financing constraints, influence green innovation decision-making (Czarnitzki & Hottenrott 2009; Jiang et al. 2010). Firstly, equity pledges worsen agency problems. After the pledge, controlling shareholders tend to shift their focus from the company's long-term goals to short-term stock price performance in order to maintain stock price stability (Chan et al. 2018). Because green innovation projects are long-term, capital-intensive, and yield low short-term returns, controlling shareholders may reduce investments in green innovation for personal gain, which is detrimental to the company's green innovation efforts (Ji et al. 2025; Manso 2011). Secondly, when the stock price approaches the margin call threshold, controlling shareholders have stronger incentives to engage in tunnelling behaviours, such as related-party transactions or fund misappropriation, to transfer corporate funds and mitigate personal losses. This may lead to the diversion of funds allocated to green innovation projects (Czarnitzki & Hottenrott 2009; Jiang et al. 2010). Thirdly, equity pledges signal negative financial health to external stakeholders, leading to difficulties in financing (Benfratello et al. 2008; Bhatia et al. 2019). As a result, banks and financial institutions increase credit thresholds and reduce loan limits. The increased external financing costs and difficulties in securing funds reduce green innovation investment. Given that green innovation relies heavily on external financing, heightened financing constraints have a significant inhibitory effect on green innovation development (Czarnitzki & Hottenrott 2009).

Based on the above analysis, the agency problems, tunnelling incentives, and increased financing constraints resulting from equity pledges by controlling shareholders will lead to insufficient investment in green innovation, creating a significant inhibitory effect. Consequently, this article proposes the following hypothesis:

H1: Controlling shareholders' equity pledges will inhibit corporate green innovation.

Methods

Model construction

In order to test the relationship between equity pledges and corporate green innovation, this article constructs the following model (Equation 1):

$$Envrpat_{it} = \beta_0 + \beta_1 PLD\_RATE_{it} + \beta_2 Control_{it} + Ind_i + Year_t + \varepsilon_{it} \quad \text{[Eqn 1]}$$

where i and t denote the firm and year, respectively, $Envrpat_{it}$ represents the level of green innovation of the firms, PLD_RATE_{it} denotes the proportion of controlling shareholders' equity pledges, and $Control_{it}$ encompasses a series of control variables. Moreover, Ind_i and $Year_t$ account for industry and year fixed effects, respectively, while ε_{it} is the random perturbation term.

Data sources

In this article, we analyse data from A-share listed companies spanning the period from 2012 to 2022 and employ quantitative empirical methods to analyse the relationship between controlling shareholders' equity pledges and corporate green innovation. The data on controlling shareholders' equity pledges and corporate financial information are sourced from the CSMAR database, while data on corporate green innovation are obtained from the CNRDS database. To enhance the robustness of the study, we implement the following data cleaning procedures: (1) Excluding samples from delisted enterprises, (2) excluding samples from Special Treatment (ST) and *ST enterprises, (3) excluding samples from the financial industry, (4) excluding samples with missing data, (5) excluding samples with anomalous financial data, such as instances where liabilities exceed assets, and (6) trim the upper and lower 1% of the samples to mitigate the influence of outliers. After data cleaning, a total of 33 279 samples were obtained.

Variable settings

Dependent variable

Enterprise Green Innovation (Envarpat). The green innovation capability of enterprises is primarily assessed through two dimensions: R&D input and innovation output. Generally, green innovation relies heavily on human and capital investments, with R&D expenditures and the number of R&D personnel positively correlating with the level of green innovation. However, the R&D expenditures and personnel data reported by listed companies do not specify whether these investments pertain to green innovation or other types of innovation, making it challenging to accurately measure the level of green innovation. To provide a clearer indication of green innovation output, the number of green patent applications filed by enterprises serves as a more direct metric. In China, patent classification includes three types: invention patents, utility model patents, and design patents. Among these, invention and utility model patents more effectively reflect the level of creativity involved in innovation. Consequently, this article uses the natural logarithm of the number of invention and utility model patents filed, plus one, as a measure of the innovation level of enterprises (Chi et al. 2023; Dong et al. 2024; Peng & Kong 2024).

Core explanatory variable: Pledge of controlling shareholders' equity (PLD_RATE)

Several studies have employed a binary variable to indicate whether or not a controlling shareholder has pledged equity in order to analyse the impact of such pledges (Hu et al. 2021; Pang & Wang 2020; Wang & Zhang 2024). However, this approach overlooks the nuanced differences in how varying levels of controlling shareholders' pledges affect firms. The influence of these pledges is likely to increase incrementally with the rising pledge ratio. To more effectively examine the impact of controlling shareholders' equity pledges on corporate green innovation, this article utilises the ratio of the number of controlling shareholders' equity pledges to their total shareholdings (PLD_RATE) in its regression analysis (Hu et al. 2021; Lee & Yeh 2004). This method allows for a more comprehensive understanding of how the extent of equity pledging influences green innovation outcomes.

Control variables

Companies with large scale, high growth potential, and strong internal control are considered to have better resource supply conditions and stronger motivation for green innovation. This is because their high visibility and good internal governance make it easier to gain policy support and attract external investment (Chan et al. 2018; Chi et al. 2023). Drawing on the existing literature (Chi et al. 2023; Dong et al. 2024; Pang & Wang 2020). This study controls for the following variables: (1) Control variables reflecting firm size characteristics (Fan & Wong 2002; Guo et al. 2023), including firm size (Size), measured by the natural logarithm of total assets; firm age (FirmAge), measured by the natural logarithm of the firm's age. (2) Control variables reflecting firm growth (Han et al. 2024; He & Huang 2017; Hu et al. 2021), including firm growth (Growth), measured by the firm's revenue growth rate; Tobin's Q (TobinQ), the ratio of market value to replacement cost. (3) Control variables reflecting the internal control level of the firm (Lee & Yeh 2004; Li et al. 2024; Su, Wan & Song 2018), including firm ownership structure (state-owned enterprise [SOE]), a dummy variable where 1 indicates state-owned control and 0 indicates non-state-owned control; ownership by the largest shareholder (Top1), the shareholding ratio of the largest shareholder; board size (Board), measured by the natural logarithm of the number of board members plus one. (4) Key financial indicators of the firm (Peng & Kong 2024; Tan et al. 2024), including leverage (Lev), measured by the ratio of book total leverage to book total assets; return on assets (ROA), calculated as the ratio of net profit to total assets.

Ethical considerations

This article followed all ethical standards for research without direct contact with human or animal subjects.

Results and discussion

Description statistic

Table 1 presents the results of descriptive statistics for the core variables in the study. The key explanatory variable, controlling shareholder pledge ratio (PLD_RATE), ranges from a minimum value of 0 to a maximum value of 1, with a mean of 0.249 and a standard deviation of 0.342. This indicates that, while the level of equity pledging by controlling shareholders is generally reasonable, there is substantial variation across firms. The explanatory variable for enterprise green innovation (EnvrPat) has a maximum value of 3.466 and a minimum value of 0, yielding a mean of 0.325 and a standard deviation of 0.725. These figures suggest that the level of green innovation among Chinese enterprises remains low and there is significant disparity in innovation levels across different firms. The average shareholding ratio of controlling shareholders is 34.27%, indicating a relatively concentrated ownership structure, which grants controlling shareholders considerable influence over corporate decisions. The other control variables show no abnormalities: the average size of enterprises is approximately 2.227 billion, the average leverage ratio is 43%, and the average return on total assets is 3.8%.

Baseline regression results

Table 2 presents the results of the benchmark regression analysing the relationship between the proportion of equity pledged by controlling shareholders and firms' green innovation. In this regression, we progressively incorporate year and industry fixed effects, as well as control variables, while employing robust standard errors to adjust the results. Column (1) does not include year fixed effects, industry fixed effects, or control variables. In contrast, column (2) introduces both year and industry fixed effects, yielding regression coefficients of −0.126 and −0.121, respectively. Both coefficients are significant at the 1% level, indicating a negative effect of controlling shareholders' equity pledges on firms' green innovation. Column (3) includes only control variables, while column (4) integrates year fixed effects, industry fixed effects, and control variables. The regression coefficients in column (4) are −0.143 and −0.07, both of which are also significant at the 1% level. The results from columns (1) through (4) collectively suggest that controlling shareholders' equity pledges diminish firms' green innovation output, thereby confirming Hypothesis H1.

TABLE 1: Descriptive statistics (N = 33 279).

Variable	Mean	SD	Min	Max
PLD_RATE	0.249	0.342	0.000	1.000
EnvrPat	0.325	0.725	0.000	3.466
Size	22.270	1.299	19.730	26.250
Lev	0.431	0.206	0.055	0.908
ROA	0.038	0.067	-0.253	0.221
Growth	0.160	0.403	-0.593	2.501
FirmAge	2.927	0.338	0.693	4.174
TobinQ	2.025	1.329	0.842	8.751
SOE	0.354	0.478	0.000	1.000
Top1	34.27	14.740	8.448	74.660
Board	2.121	0.200	1.099	2.890

Min, minimum; Max, maximum; SD, standard deviation.

Robustness test

To enhance the reliability of the empirical results, we conducted a series of robustness tests. This article will re-examine the relationship between controlling shareholders' equity pledges and corporate green innovation using Instrumental Variable Estimation. Furthermore, we will substitute key indicators, incorporate lagged explanatory variables, and apply alternative model specifications. These strategies aim to mitigate the potential effects of endogeneity issues and omitted variable bias on our conclusions, ensuring a more robust analysis of the relationship in question.

Instrumental variable estimation

To address potential issues of reverse causation, omitted variables, and endogeneity related to the selection of samples for controlling shareholders' equity pledges, this article employs the instrumental variable (IV) method to ensure the reliability and validity of the results. Following established research methods, we construct PLD_RATEIV as an instrumental variable and employ a two-stage least squares (2SLS) regression model for our analysis. The IV is based on the average number of equity pledges made by controlling shareholders of enterprises within the same industry and province. This approach is founded on the observation that firms within the same industry typically share similar governance characteristics and financial structures, leading to comparable behaviours in controlling shareholders' equity

TABLE 2: Baseline regressions.

Variable	Sub-variable	*EnvrPat*			
		(1)	(2)	(3)	(4)
PLD_RATE	Coefficient	-0.126***	-0.121***	-0.143***	-0.070***
	Robust *t*-statistic	-12.030	-11.830	-12.150	-6.130
Size	Coefficient	-	-	0.111***	0.121***
	Robust *t*-statistic	-	-	22.170	23.920
Lev	Coefficient	-	-	0.109***	0.126***
	Robust *t*-statistic	-	-	4.870	5.630
ROA	Coefficient	-	-	0.314***	0.471***
	Robust *t*-statistic	-	-	5.130	7.870
Growth	Coefficient	-	-	-0.036***	-0.053***
	Robust *t*-statistic	-	-	-4.430	-6.620
FirmAge	Coefficient	-	-	-0.139***	-0.089***
	Robust *t*-statistic	-	-	-11.650	-6.770
TobinQ	Coefficient	-	-	0.015***	0.014***
	Robust *t*-statistic	-	-	5.240	4.590
SOE	Coefficient	-	-	-0.081***	0.024**
	Robust *t*-statistic	-	-	-8.050	2.360
Top1	Coefficient	-	-	-0.001***	0.000
	Robust *t*-statistic	-	-	-4.810	0.710
Board	Coefficient	-	-	0.017	0.090***
	Robust *t*-statistic	-	-	0.770	4.280
Constant	Coefficient	0.356***	0.003	-1.742***	-2.685***
	Robust *t*-statistic	70.080	0.130	-15.480	-22.730
Year fixed effect	-	No	Yes	No	Yes
Industry fixed effect	-	No	Yes	No	Yes
Observations	-	33 279	33 279	33 279	33 279
R-squared	-	0.004	0.133	0.041	0.179

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

pledging. In addition, the external financing environment faced by firms in the same province is generally more analogous, making their equity pledging strategies susceptible to similar influences. Importantly, the mean value of controlling shareholders' equity pledges among firms in the same industry and province reflects only the characteristics of that industry and region; it does not directly impact the green innovation capabilities of individual firms. Thus, this IV satisfies the principles of relevance and exogeneity, effectively mitigating the risk of endogeneity. As indicated by the results presented in Table 3, the findings derived from the IV method remain robust. This outcome further supports the effectiveness of our model and provides a more robust empirical foundation for understanding the relationship between controlling shareholders' equity pledges and corporate green innovation.

Replacing core explanatory variables

Furthermore, this article utilises a technique of replacing explanatory variables to provide additional validation for the research findings. Firstly, we introduce the ratio of the total number of equity pledges made by controlling shareholders to the total equity of enterprises as a new explanatory variable for empirical analysis. Secondly, we use a dummy variable indicating whether the controlling shareholder has pledged shares to conduct the test. The result in column (1) of Table 4 represents the regression analysis of the ratio of the total amount of shares pledged by the controlling shareholder to the firm's total equity. The results indicate that an increase in the ratio of controlling shareholders' equity pledges to total equity is associated with a corresponding decline in the level of green innovation exhibited by firms. The result in column (2) of Table 4 presents the regression outcome for the dummy variable indicating whether the controlling shareholder has pledged shares. The results show that when the controlling shareholder pledges shares, the firm's green innovation output is significantly suppressed. This finding reinforces the validity of hypothesis H1, suggesting that controlling shareholders' equity pledges significantly influence firms' innovation capabilities. The application of this substitution method not only enhances the flexibility of our model but also offers a more comprehensive perspective for examining the impact of controlling shareholders' equity pledges on corporate green innovation.

TABLE 3: Robustness tests: Instrumental variables method.

Variable	Sub-variable	(1) *PLD_RATE*	(2) *EnvrPat*
PLD_RATEIV	Coefficient	0.729***	-
	Robust *t*-statistic	67.940	-
PLD_RATE	Coefficient	-	-0.079**
	Robust *t*-statistic	-	-2.540
Constant	Coefficient	-0.055	-2.685***
	Robust *t*-statistic	-1.280	-22.750
Controls	-	Yes	Yes
Year fixed effect	-	Yes	Yes
Industry fixed effect	-	Yes	Yes
Observations	-	33 279	33 279
R-squared	-	0.355	0.178

Note: ***,**,*, statistically significant at the 1% level, 5% and 10% levels, respectively.

Lagging the core explanatory variable

This article further investigates the potential impact of equity pledges by controlling shareholders on firms' future levels of green innovation. To achieve this, we conducted lagged analyses of the core explanatory variables, specifically examining lag 1 and lag 2 effects. The empirical results presented in columns (3) to (4) of Table 4 reveal a significant negative correlation between controlling shareholders' equity pledges and firms' green innovation levels over the subsequent 2-year period. These findings suggest that the equity pledging behaviour of controlling shareholders continues to exert a dampening influence on firms' innovation capabilities in the near term. However, it is important to note that this inhibitory effect gradually diminishes over time. In other words, while controlling shareholders' equity pledges negatively impact firms' green innovation in the short term, this effect appears to lessen with extended time. This finding implies that firms, when faced with equity pledges by controlling shareholders, may adjust their future business

TABLE 4: Robustness tests.

Variable	Sub-variable	EnvrPat					
		(1)	(2)	(3)	(4)	(5)	(6)
PLD_RATE2	Coefficient	-0.171***	-	-	-	-	-
	Robust *t*-statistic	-4.820	-	-	-	-	-
PLD_DUM	Coefficient	-	-0.023***	-	-	-	-
	Robust *t*-statistic	-	-2.990	-	-	-	-
L.PLD_RATE	Coefficient	-	-	-0.067***	-	-	-
	Robust *t*-statistic	-	-	-5.270	-	-	-
L2.PLD_RATE	Coefficient	-	-	-	-0.064***	-	-
	Robust *t*-statistic	-	-	-	-4.690	-	-
PLD_RATE	Coefficient	-	-	-	-	-0.024**	-0.132***
	Robust *t*-statistic	-	-	-	-	-2.030	-5.960
Constant	Coefficient	-2.690***	-2.771***	-2.788***	-2.895***	-1.440***	-3.758***
	Robust *t*-statistic	-22.760	-23.610	-21.140	-19.940	-8.680	-18.680
Controls	-	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effect	-	Yes	Yes	Yes	Yes	Yes	Yes
Industry fixed effect	-	Yes	Yes	Yes	Yes	Yes	Yes
Observations	-	33 279	33 279	28 155	24 300	33 279	17 266
R-squared	-	0.178	0.177	0.185	0.186	0.158	0.167

Note: ***,**,*, representing statistical significance at the 1%, 5% and 10% levels, respectively.

strategies to mitigate this external pressure, thereby lessening the negative impact on innovation. This dynamic analysis offers a more nuanced understanding of the relationship between equity pledges by controlling shareholders and firms' green innovation, highlighting the importance of temporal factors in this relationship.

Enterprise fixed effects model

In column (5) of Table 4, we employed a fixed-effects model to conduct further empirical tests. The regression results indicate that the coefficient of PLD_RATE remains significantly negative, suggesting that the inhibitory effect of controlling shareholders' equity pledges on firms' green innovation levels is persistent. This finding not only corroborates our previous results but also underscores the enduring nature of the influence that controlling shareholders' equity pledging behaviour has on firms' innovation capabilities. The use of a fixed-effects model allows us to control for unobserved individual characteristics, providing a more accurate representation of the causal relationship between controlling shareholders' equity pledges and firms' green innovation. Furthermore, this approach reveals more precise insights into the impact of equity pledges within diverse intra-firm contexts. The robustness of the fixed-effects model further validates our original hypothesis, reinforcing the conclusion that controlling shareholders' equity pledges exert a significant inhibitory effect on firms' green innovation.

Exclusion of firms without patents

In this study, we exclude from our empirical analysis firms that have never produced patents for green innovations. It is possible that these firms exhibit certain weaknesses in their internal governance, leading to more aggressive equity pledging by their controlling shareholders for personal gain. Such behaviour may skew the negative relationship between controlling shareholders' equity pledges and firms' green innovation capabilities in the benchmark regression. By excluding these firms, we can better control for potential biases and enhance the stability of our experimental results. The findings presented in column (6) of Table 4 demonstrate that our results remain robust following this sample adjustment. This suggests that the inhibitory effect of controlling shareholders' equity pledges on firms' green innovation is significant even after accounting for possible confounding influences.

Mechanism analysis

Previous studies have provided substantial empirical evidence regarding the relationship between controlling shareholders' equity pledges and corporate green innovation. However, the underlying mechanisms remain unexplored. This section aims to elucidate the channels through which these equity pledges influence green innovation, effectively uncovering the black box. To examine the mediating effects of controlling shareholders' equity pledges on firms' green innovation, this article constructs the following mediation model:

$$Envrpat_{it} = \beta_0 + \beta_1 PLD\_RATE_{it} + \beta_2 Control_{it} + Ind_i + Year_t + \varepsilon_{it} \quad \text{[Eqn 2]}$$

$$Mediator_{it} = \gamma_0 + \gamma_1 PLD\_RATE_{it} + \gamma_2 Control_{it} + Ind_i + Year_t + \varepsilon_{it} \quad \text{[Eqn 3]}$$

$$Envrpat_{it} = \theta_0 + \theta_1 PLD\_RATE_{it} + \theta_2 Mediator_{it} + \theta_3 Control_{it} + Ind_i + Year_t + \varepsilon_{it} \quad \text{[Eqn 4]}$$

In this study, $Mediator_{it}$ represents the mediator variable. This article examines three mechanisms: 'corporate ESG performance', 'financing constraints', and 'tunnelling'.

Environmental, social, and governance performance mechanism

An ESG rating serves as a vital tool for assessing a company's ESG performance in its operations. This rating not only reflects the company's sustainability efforts but is also closely linked to the degree to which managers prioritise ecological and social responsibility. Unlike traditional performance management, ESG performance is not directly associated with a company's short-term economic outcomes. For managers, enhancing ESG performance provides primarily reputational incentives, which can yield significant long-term benefits for both the firm and the manager. Research indicates that equity pledging by controlling shareholders often leads to short-sighted business practices, resulting in diminished attention to ecological and social responsibilities. This short-sighted behaviour hampers companies' ability to achieve better ESG scores and affects their overall sustainability.

As governmental focus on sustainable development intensifies, the external incentives and monitoring mechanisms associated with ESG scores also increase. This dual role of incentives and monitoring has a direct influence on promoting green innovation within enterprises (Tan et al. 2024). Studies have explored how firms' ESG performance positively incentivises green innovation processes. Findings reveal that higher ESG scores indicate a greater commitment to environmental protection and social responsibility, which enhances a firm's green reputation. This improved reputation attracts more interest from green investment funds and fosters cooperation with other firms engaged in green innovation. Environmental, Social, and Governance performance is intricately connected to external incentives. Companies with low ESG ratings often face difficulties in securing green credit and government subsidies, which are crucial sources of funding for green innovation. Consequently, poor ESG performance can lead to challenges in accessing resources, thereby inhibiting a firm's capacity for green innovation.

In measuring ESG performance, this article adopts the Huazheng ESG rating as a proxy variable for corporate ESG

performance. The Huazheng ESG ratings are categorised into nine grades, ranging from 'AAA' to 'C', which this article quantifies as '9-1' to construct a quantitative index of corporate ESG ratings. The analytical results in columns (1) to (2) of Table 5 further support the theoretical framework of ESG ratings. The data indicate a significant negative correlation between controlling shareholders' equity pledges and firms' ESG scores; specifically, a higher proportion of equity pledges by controlling shareholders correlates with lower ESG scores, which subsequently inhibits firms' green innovation capabilities. This finding underscores the necessity of balancing short-term interests with long-term sustainable development goals in corporate governance and shareholder structures.

Financing constraint mechanism

A portion of the funds allocated by enterprises for green innovation comes from external financing (Czarnitzki & Hottenrott 2009). This financing is essential for providing the necessary ongoing inputs for green innovation projects. However, when enterprises encounter financing constraints, they often prioritise short-term projects over long-term investments. This shift occurs because green innovation projects typically require longer timelines and involve greater uncertainty. As financing constraints intensify, firms may experience a dual impact: insufficient funding coupled with reductions in R&D spending, further inhibiting their investment in green innovation.

While equity pledging is a common financing tool, it carries the potential risk of exacerbating corporate financing constraints. When controlling shareholders secure financing through equity pledges, the funds are not always directed towards alleviating the firm's financial pressures. Research indicates that a significant portion of the funds obtained through equity pledges is often used for personal consumption (Pang & Wang 2020) rather than being reinvested into the enterprise's operations. This misallocation not only hinders the enterprise's development but also undermines its capacity to manage financial pressures during critical periods. Furthermore, when a controlling shareholder makes an equity pledge, the risk of the share price falling below the pledged amount can trigger a chain reaction, resulting in a collapse of share prices and a transfer of control. This situation can weaken the enterprise's financing ability and further exacerbate its financing constraints.

To investigate this phenomenon, this article employs established research methods and utilises the Kaplan and Zingales (KZ) indicator as a proxy variable for corporate financing constraints (Kaplan & Zingales 1997). A higher value of this indicator indicates more severe financing constraints faced by the enterprise. Regression results presented in columns (3) and (4) of Table 5 reveal a positive correlation between the equity pledges of controlling shareholders and corporate financing constraints. Additionally, there is a negative correlation between financing constraints and corporate green innovation. These findings suggest that the equity pledging behaviour of controlling shareholders exacerbates the financing constraints faced by enterprises, ultimately leading to a decline in both their investment levels and their commitment to green innovation.

Controlling shareholder tunnelling mechanism

Because of their control advantages and information asymmetries, controlling shareholders can effectively conceal tunnelling activities. When both external and internal supervision are insufficient, detecting such behaviour becomes challenging (Liu & Tian 2012). Once tunnelling occurs, it can have severe consequences for the enterprise, particularly hindering its green innovation efforts. As previously noticed, corporate green innovation relies heavily on resource allocation and requires ongoing financial support. However, tunnelling by controlling shareholders can deplete enterprise resources, resulting in internal financial imbalances and liquidity shortages, which ultimately impede the maintenance of green research expenditures.

TABLE 5: Mechanism analysis.

Variable	Sub-variable	(1) *ESGscore*	(2) *EnvrPat*	(3) *KZ*	(4) *EnvrPat*	(5) *Tunnel*	(6) *EnvrPat*
PLD_RATE	Coefficient	-0.603***	-0.032***	0.358***	-0.066***	0.005***	-0.068***
	Robust *t*-statistic	-30.940	-2.690	15.230	-5.770	10.450	-5.920
ESGScore	Coefficient	-	0.062***	-	-	-	-
	Robust *t*-statistic	-	15.610	-	-	-	-
KZ	Coefficient	-	-	-	-0.011***	-	-
	Robust *t*-statistic	-	-	-	-3.740	-	-
Tunnel	Coefficient	-	-	-	-	-	-0.317**
	Robust *t*-statistic	-	-	-	-	-	-2.430
Constant	Coefficient	-0.830***	-2.619***	2.265***	-2.661***	0.019***	-2.681***
	Robust *t*-statistic	-5.240	-22.090	11.120	-22.540	4.440	-22.670
Controls	-	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effect	-	Yes	Yes	Yes	Yes	Yes	Yes
Industry fixed effect	-	Yes	Yes	Yes	Yes	Yes	Yes
Observations	-	32 642	32 642	33 278	33 278	33 224	33 224
R-squared	-	0.211	0.184	0.688	0.179	0.164	0.179

Note: ***,**,*, representing statistical significance at the 1%, 5% and 10% levels, respectively.

The pledging of controlling shareholders' equity intensifies their motivation to engage in tunnelling. Controlling shareholders experience differing incentives from their control and cash flow rights, and as these rights become misaligned, the tunnelling effect increases. When a majority shareholder pledges equity, the separation between cash flow rights and control rights widens, further heightening the propensity for tunnelling (Jiang et al. 2010). Additionally, given the high financing costs associated with equity pledging, this may become a last resort for controlling shareholders seeking funding. Consequently, if the majority shareholder wishes to secure additional financing, they may resort to tunnelling as a means to obtain necessary funds.

Consistent with established practices, we measure the extent of tunnelling using the ratio of 'other receivables to total firm assets' (Jiang et al. 2010; Liu & Tian 2012). The regression results presented in columns (5) and (6) of Table 5 indicate that the tunnelling effect progressively intensifies as the proportion of controlling shareholders' equity pledges increases, thereby inhibiting the level of green innovation within firms.

Heterogeneity analysis

Heterogeneity of controlling shareholder pledge ratios

Previous studies have demonstrated that a higher proportion of equity pledged by controlling shareholders negatively impacts firms' levels of green innovation. However, the effects of high and low pledge ratios may differ. Firstly, Chinese firms often exhibit concentrated ownership, with controlling shareholders holding significant equity stakes. As the equity pledge ratio increases, the risk of control transfer becomes more pronounced. When the pledge ratio is low, a decline in share prices – absent margin calls that would lead to liquidation – does not typically trigger a transfer of control. Consequently, as the risk of control transfer is minimal, controlling shareholders still have the incentive to invest in green innovation, mitigating concerns related to their potential short-sightedness and conservative management practices. Secondly, controlling shareholders with lower equity pledges face fewer financing constraints. In situations where cash flow is limited, they can continue to pledge additional equity to raise necessary funds. In contrast, shareholders with higher pledge ratios may lose the ability to secure further financing. Thirdly, a high proportion of equity pledges exacerbates the separation between controlling shareholders' cash flow rights and their control rights. This situation can intensify motivations for 'capital appropriation' and 'connected transactions', increasing the likelihood that controlling shareholders may pursue personal gains at the expense of the enterprise's interests, ultimately hindering corporate green innovation. To verify the heterogeneity of equity pledge ratios, we analyse the differences between high and low equity pledge ratios among controlling shareholders. We categorise the ratios into high and low pledge groups based on their comparison to the sample mean. Columns (1) and (2) of Table 6 present the characteristics of these groups. The results indicate that the impact of controlling shareholders' equity pledges on corporate green innovation is significant only in firms with a high proportion of equity pledges. In contrast, when the proportion of controlling shareholders' pledges is low, the inhibitory effect on corporate green innovation is negligible.

Heterogeneity of heavily polluting enterprises

As China's focus on environmental issues has intensified, relevant laws and regulations have been continuously refined, and oversight of polluting enterprises has been strengthened. Following the introduction of policies such as 'carbon neutrality' and 'carbon peaking', environmental protection agencies worldwide have imposed stringent controls on carbon emission targets within their jurisdictions. This increase in external environmental regulation has significantly impacted the management of polluting enterprises. For heavily polluting companies, environmentally harmful production activities can lead to higher environmental taxes, increasing production costs and diminishing market competitiveness. Moreover, these companies may face fines and production suspensions. An effective strategy for reducing corporate pollution is through green innovation. While China enforces strict environmental policies, it also promotes green finance and subsidies, aiming to assist heavily polluting enterprises in rapidly transforming their operations to reduce carbon emissions. Consequently, after pledging equity in heavily polluting firms, controlling

TABLE 6: Heterogeneity analysis.

Variable	Sub-variable	*EnvrPat*					
		(1) High pledge	(2) Low pledge	(3) Polluting	(4) Non-polluting	(5) SOE	(6) Non-SOE
PLD_RATE	Coefficient	-0.148***	0.066	-0.017	-0.087***	-0.061*	-0.093***
	Robust *t*-statistic	-5.500	1.260	-0.780	-6.540	-1.830	-7.350
Constant	Coefficient	-1.904***	-3.034***	-3.299***	-2.516***	-3.251***	-2.188***
	Robust *t*-statistic	-9.730	-20.560	-13.720	-18.340	-16.180	-14.500
Controls	-	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effect	-	Yes	Yes	Yes	Yes	Yes	Yes
Industry fixed effect	-	Yes	Yes	Yes	Yes	Yes	Yes
Observations	-	11 635	21 644	7578	25 701	11 774	21 505
R-squared	-	0.170	0.193	0.175	0.182	0.246	0.166

Note:***,**,*, representing statistical significance at the 1%, 5% and 10% levels, respectively.
SOE, state-owned enterprise.

shareholders maintain a strong incentive to foster green innovation. This motivation stems from enhanced external supervision and the necessity for firms to undertake swift transformations to comply with regulatory standards for continued operations. Column (3) of Table 6 presents regression results for heavily polluting firms, revealing that the inhibitory effect of controlling shareholders' equity pledges on green innovation in these companies is not significant. In contrast, this inhibitory effect is evident in non-heavily polluting firms, as indicated in column (4). These findings suggest that heavily polluting enterprises exhibit a greater demand for green innovation, investing in such projects to lower carbon emissions and ensure normal production and operation. This investment effectively offsets the negative impact of equity pledges on their green innovation efforts. Conversely, non-high-polluting enterprises are more susceptible to the influences of equity pledges on their innovation activities.

Heterogeneity of SOE

In China, the nature of property rights significantly influences the resource endowment of firms. State-owned enterprises typically dominate their industries, benefiting from substantial advantages in terms of size and staffing. On the one hand, SOEs often maintain close relationships with local governments, allowing them to leverage their political connections to secure substantial loans. As a result, the pledging of majority shareholders' equity does not typically result in severe financing constraints. When additional equity is needed, the strong ties between the enterprise and local government, along with financial institutions, facilitate access to loans, minimising the risk of control transfer. On the other hand, SOEs are more likely to receive government green subsidies and related policy support because of their ownership structure. These advantages can mitigate some of the negative effects that equity pledges may have on green innovation. Furthermore, SOEs generally have stringent internal controls and robust corporate governance systems. Changes to a firm's business strategy or investment direction typically require a series of formal meetings and discussions, preventing majority shareholders from unilaterally altering business practices to suit their interests. In addition, majority shareholders of SOEs are subject to stricter external supervision. The discovery of 'tunneling' behaviour – wherein shareholders misappropriate resources for personal gain – can result in severe consequences. Consequently, the costs associated with 'tunneling' for majority shareholders in SOEs are higher compared to those in non-state-owned enterprises, thereby reducing the likelihood of such behaviour. Columns (5) and (6) of Table 6 present the regression results for state-owned and non-state-owned holdings, respectively. Our findings indicate that in the sample of state-owned firms, the inhibitory effect of controlling shareholders' equity pledges on green innovation is insignificant. In contrast, this inhibitory effect is significant in non-state-owned firms.

Conclusion

By utilising data from Chinese A-share listed companies, this article examines the relationship between controlling shareholders' equity pledges and corporate green innovation, as well as the mechanisms underlying this influence. The findings indicate that controlling shareholders' equity pledges significantly inhibit the green innovation capacity of firms. On the one hand, concerns about potential control transfer resulting from declining share prices lead controlling shareholders to adopt conservative business strategies during the pledge period. This focus on short-term profitability often results in reduced R&D expenditures, which is detrimental to the firms' green innovation efforts. On the other hand, when the returns from corporate control surpass those from cash flow, the incentive for controlling shareholders to pursue green innovation diminishes significantly, resulting in the encroachment effect. This effect is further intensified as the proportion of controlling shareholders' equity pledges increases, ultimately impairing the firm's capacity for green innovation.

In the empirical analysis, we utilise the ratio of controlling shareholders' equity pledges to their own shareholdings, alongside the number of green patent applications by enterprises, to examine the relationship between these variables. The empirical results confirm the inhibitory effect of controlling shareholders' equity pledges on corporate green innovation. In addition, this article conducts robustness tests employing the IV method, replacing core explanatory variables, applying a fixed effects model, and excluding samples of firms that have never applied for green patents.

In further analyses, we provide an in-depth discussion of the mechanisms by which equity pledges influence green innovation. We identify three key channels through which controlling shareholders' equity pledges can affect firms' green innovation efforts. Firstly, during the pledge period, controlling shareholders may deprioritise investments in the firms' ESG performance. This neglect weakens the firms' ability to secure external green funding, ultimately diminishing their capacity for green innovation. Secondly, equity pledges increase the risk of share price crashes and the potential for changes in control, leading to heightened corporate uncertainty. This uncertainty can raise lenders' concerns regarding the firm, exacerbating financing constraints and further inhibiting green innovation. Finally, tunnelling represents another significant channel affecting green innovation. Equity pledges intensify the separation between controlling shareholders' cash flow rights and control rights, increasing the likelihood of tunnelling behaviour. As the tunnelling effect rises, it further undermines green innovation initiatives within the firm.

Based on these findings, this article proposes the following policy insights:

Firstly, government regulators should enhance oversight of controlling shareholders' equity pledges by strictly

controlling the flow of pledged funds and improving the transparency of related information disclosure. Additionally, authorities should strengthen the enforcement of regulations against violations by controlling shareholders. By increasing the costs associated with illegal tunnelling activities, regulators can reduce the incentive for controlling shareholders to appropriate resources, thereby mitigating the risk of stock price collapses.

Secondly, it is essential to facilitate financing for corporate green innovation projects by utilising green industry fund platforms to establish two-way communication channels between enterprises and funding sources. This approach can reduce the matching costs for both parties, making it easier for projects to secure funding. In addition, efforts should be made to enhance the transformation of green innovations into tangible results. By creating a new virtuous cycle of 'financing – input – output – refinancing', we can strengthen the funding and support for enterprises, ultimately improving their capacity for green innovation.

Thirdly, it is important to expand the scale of green subsidies. The government should enhance financial and technical support for corporate green innovation projects by providing subsidies to eligible initiatives. In addition, selecting and cultivating a number of high-quality enterprises with strong green innovation capabilities can help foster industry leaders. Furthermore, guiding credit funds to support green innovation is crucial. Expanding the availability of green credit, reducing lending rates, and increasing liquidity for enterprise green innovation projects will provide essential financial resources, enabling firms to invest more effectively in sustainable practices.

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Authors' contributions

L.L. drafted the manuscript and compiled the references. P.L. reviewed and critiqued the manuscript. All authors participated in the conception and design of the study, provided feedback on earlier versions of the manuscript, and approved the final version.

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Data availability

The authors declare that all data that support this research article and findings are available in the article and its references; further inquiries can be directed to the corresponding author, P.L.

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