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Green innovation under multiple pressures: examining financial constraints, ESG performance, and environmental regulations

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ABSTRACT

This study investigates the role of environmental, social, and governance (ESG) performance in reshaping the relationship between financial constraints and green innovation among Chinese listed firms from 2010 to 2023. We examine the double-edged sword hypothesis that financial constraints affect innovation differently depending on firms' ESG performance. Our baseline results confirm that financial constraints significantly reduce green innovation. However, we find a significant positive interaction of ESG and financial constraints on green innovation, indicating that ESG performance weakens or offsets the negative impact of financial constraints on green innovation. Furthermore, environmental regulations amplify this moderation effect through a positive triple interaction, suggesting that regulatory pressure strengthens ESG's role in transforming constraints into innovation drivers. Moreover, the positive interaction between ESG and financial constraints is stronger in state-owned enterprises and high-polluting industries. These findings suggest that ESG performance can transform financial constraints from barriers into innovation drivers. We recommend that policymakers prioritize strengthening firms' sustainability capabilities through targeted financial and regulatory instruments, rather than implementing uniform policies or regulatory frameworks without considering the firms' ESG capabilities.

Introduction

Emerging economies are transitioning to green technologies to progress toward carbon neutrality while sustaining economic growth (Zheng et al., 2025). Several research studies have been conducted to analyze the determinants of green innovation, indicating that these determinants vary in emerging economies (Pradhan et al., 2025). However, fewer studies have examined this relationship from the perspective of financial constraints and ESG performance. The theoretical literature offers competing perspectives, showing that financial constraints lower green innovation, while potentially enhancing research and development efficiency that positively affects green innovation (D. Zhang & Jin, 2021). The resource constraint perspective is validated by the large capital requirements of $115 trillion through 2050 for the energy system transformation, with China requiring $46 trillion and other emerging economies needing $69 trillion, highlighting the imbalance between innovation goals and financial resources (Cuming, 2024). Therefore, the lack of financial resources can reduce innovation efficiency and decrease green productivity (Li et al., 2024; D. Zhang & Vigne, 2021).

Regulatory pressures and ESG considerations are also key drivers of green innovation, particularly when environmental regulations impose compliance requirements that stimulate innovation gains exceeding compliance costs, consistent with the Porter Hypothesis (D. Peng & Kong, 2024; Porter & Van Der Linde, 1995). In this context, a higher ESG performance shows the firm's commitment to sustainability through corporate social responsibility and internal governance to improve green technological innovation (Xu & He, 2025), leading to lower emissions and helping achieve carbon neutrality goals (K.-C. Zhang et al., 2024). A regulatory framework and corporate governance with a focus on sustainability foster green innovation. Empirical evidence supports the Porter Hypothesis, indicating that environmental regulations have a significant impact on green patent filings, with stronger effects on invention patents compared to utility patents (Cui et al., 2022; H. Peng et al., 2021). Therefore, firms with strong ESG commitments and regulatory compliance achieve higher green innovation outcomes despite financial limitations.

Based on the above discussion, this study aims to investigate the association between financial constraints, ESG performance, environmental regulations, and green innovation for Chinese listed firms from

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2010 to 2023. This study focuses on China, the world's largest emerging economy, which combines substantial environmental challenges with rapidly evolving regulatory frameworks. Firms listed on the Shanghai and Shenzhen stock exchanges face multiple pressures, including capital constraints, stringent government environmental regulations, and high ESG expectations from foreign investors. The combination of financial, regulatory, and ESG pressures gives us a unique empirical context to examine how ESG performance affects the relationship between financial constraints and green innovation. Moreover, the heterogeneity in ownership structures and political connections further enables analysis of differential resource access and regulatory responsiveness (D. Peng & Kong, 2024; Y. Sun & Yang, 2024). This study contributes to existing literature in different ways: (1) We model the interactive effects of financial constraints, ESG performance, and environmental regulation on green innovation, addressing the limitation of prior work that treats these factors as independent variables (e.g., Z. Wang et al., 2025). (2) We measure green innovation using both invention and utility model patents, recognizing that aggregating only invention patents would miss incremental innovations while counting all patents equally would overstate symbolic compliance (Lan et al., 2025; D. Zhang, 2022). (3) We incorporate industry-level regulatory variation and estimate triple interactions among constraints, ESG, and regulation.

Literature review

ESG performance and green innovation

The literature shows a positive relationship between ESG performance and green innovation, showing that firms with high ESG performance advance more environmental technologies as compared to firms with lower ESG performance (Gan & Yusupov, 2025; Xu & He, 2025; Zhu et al., 2025). ESG-oriented firms have improved access to financial resources (Gan & Yusupov, 2025), have better stakeholder relationships (Zhu et al., 2025), and higher technological capabilities (Xu & He, 2025). Gan and Yusupov (2025) showed that ESG performance in the supply chain positively influences green innovation by reducing financial constraints, enhancing supply chain efficiency, and stabilizing the supply-demand relationship. The results of their study also showed that environmental and social dimensions exert stronger effects relative to governance components, suggesting dimensional heterogeneity in ESG impact on innovation. Zhu et al. (2025) showed that shareholder activism mechanisms, including institutional investors' field survey and board appointments, enhance the positive relationship between ESG and green innovation. Moreover, a study on the ESG rating divergence has shown negative impacts on green innovation activities, with disagreement among rating agencies diminishing corporate environmental technology investments (Zhu et al., 2025). Mirza et al. (2025) revealed that banks exposed to high-ESG firms improve their performance, suggesting ESG firms' operational advantages.

D.Wang and Wang (2025) found that ESG disclosure enhances green innovation by easing financing constraints and reducing agency costs, with local government environmental attention showing an inverted U-shaped moderating effect, indicating optimal disclosure levels beyond which regulatory scrutiny may impede innovation. Hou et al. (2025) showed that green supply chain knowledge networks positively influence ESG performance through green technology innovation mediation, with knowledge integration capability serving as a critical boundary condition determining network exploitation effectiveness. The customer-supplier dynamics are equally important, as F.Wang et al. (2025) revealed that customer ESG discourse power enhances supplier green innovation through green convergence mechanisms—cognitive, behavioral, and managerial, with dependent and trusted customer relationships amplifying these effects while stable relationships demonstrate positive moderation. These findings indicate that ESG performance creates innovation spillovers through inter-organizational networks and stakeholder interactions, indicating that sustainability practices create innovation eco-systems extending beyond organizations.

Financial constraints and green innovation

The impact of financial constraints on green innovation varies significantly across firms and institutional characteristics. Zhang and Jin (2021) showed that, in contrast to theoretical rationale, financial constraints enhance green innovation efficiency by forcing firms to optimize resource allocation, with an improved R&D investment efficiency as a result of financing constraints. These finding challenges conventional views by demonstrating that modest financial constraints may increase innovation performance. Moreover, Wang and Zhang (2022) showed that green finance reform significantly promotes innovation by alleviating financing barriers while simultaneously enhancing environmental information disclosure. Tang et al. (2023) also found that digital finance development mitigates constraint effects, particularly for state-owned enterprises and large firms, suggesting that alternative financing channels can offset traditional capital barriers..

The impact of financial constraints on green innovation cannot be understood without considering the institutional environment. Su et al. (2023) studied green credit policy to show that institutional pressures transform financing constraints from innovation barriers into catalysts by forcing internal resource reallocation toward environmental technologies. Their study further showed that the linkage between green credit policy and financial barriers is particularly pronounced for firms that are more financially reliant on banks. Furthermore, Rao et al. (2022) studied green bonds and showed that their issuance provides direct financing and also signals environmental commitment, attracting additional resources and enhancing innovation. Financial constraints' impact depends on firms' access to alternative financing mechanisms and their capacity to leverage institutional support systems (Hu et al., 2023; Tan & Zhu, 2022).

Environmental regulations and green innovation

He et al. (2025) demonstrated that Green Credit Policy significantly enhances firms' environmental innovation output, with a causal relationship operating through the decrease and reduction of financial constraints and costs. The effectiveness of environmental regulations in promoting green innovation exhibits substantial heterogeneity across firm characteristics and institutional contexts, Shi and Zhou (2024) revealed that government R&D subsidies, when combined with strengthened environmental regulation, create synergistic effects that amplify green innovation, with financing constraints and costs serving as mediating variables. Moreover, Sun et al. (2024) revealed that while negative environmental performance feedback induces significant green innovation, this effect is positively moderated by both external regulations (government environmental regulation and public environmental concern) and internal incentives (executive equity incentive).

The implementation of specific environmental policies creates differentiated impacts across industries and ownership structures, indicating the linkage between regulatory design and firm-specific capabilities. Chang and Wang (2024) demonstrated that ESG rating events function as a form of soft market regulation, significantly promoting corporate green technology innovation by reducing financial barriers and managerial myopia, with a more pronounced effect in state-owned enterprises. Wei et al. (2025) also showed that China's new environmental protection law enhances the overall ESG performance of heavy polluting enterprises, though it paradoxically triggers strategic green innovations and financing constraints that adversely affect corporate social responsibility fulfillment and governance enhancement. Based on these findings, we conclude that environmental regulations shape green innovation through both intended and unintended mechanisms.

Methodology

Data and variables

This study selected firms listed on the Shenzhen and Shanghai Stock Exchanges from 2010 to 2023. Our sample period captures several major regulatory shocks, including China's revised Environmental Protection Law (2015), the launch of the national carbon market (2021), and the introduction of mandatory ESG disclosure requirements. Data sources include the China Stock Market & Accounting Research (CSMAR) database for financial indicators, the CNRDS database for patent information, and the SynTao Green Finance database for ESG ratings. In this study, we have excluded financial firms due to their distinct regulatory environment and capital structure.

Green innovation is measured using the logarithm of one plus the firm's total green patent applications, where total green patents comprises the sum of invention and utility model patents in environmental technologies, including both invention and utility model patents filed independently or jointly. The key independent variable in this study is financial constraints (FC) and is measured through a standardized composite index combining leverage, profitability, cash holdings, credit access, and trading status indicators. Our financial constraint index aggregates binary indicators for high leverage (>0.6), negative profitability, low cash holdings (<0.1), credit restrictions, and ST/PT designation. This approach captures constraints more comprehensively compared to using a single indicator, with standardization facilitating interpretation. ESG performance is the moderating variable in this study, which enables us to examine how sustainability practices modify the constraint-innovation relationship.

We measured environmental regulation intensity (Env_Reg) at the industry level using a four-tier scale (0–3), with heavy-polluting industries (mining, chemicals, metals) assigned the highest stringency and other sectors scaled according to their pollution intensity. The control variables in this study include are size (logarithm of total assets), leverage (debt-to-asset ratio), ownership structure, institutional ownership percentage, analyst coverage, Tobin's Q, board independence ratio, and fixed asset intensity.

Econometric model

To examine the effect of financial constraints on green innovation conditional on ESG performance, we put forward the following model:

$$GI_{it} = \beta_0 + \beta_1 FC_{it} + \beta_2 ESG_{it} + \beta_3 (FC \times ESG)_{it} + \gamma X_{it} + \mu_i + \lambda_t + \epsilon_{it}$$

Where subscripts i and t denote firm and year, respectively, X_{it} represents the vector of control variables, u_i captures industry fixed effects, λ_t represents year fixed effects, *and* ϵ_{it} is the error term. The coefficient β_1 captures the baseline effect of financial constraints on green innovation, while β_3 reveals how ESG performance moderates this relationship between financial constraints and green innovation. A significant positive β_3 value would support our hypothesis that high ESG performance transforms financial constraints from impediments into innovation catalysts.

To investigate the triple interaction effect incorporating environmental regulations, we extend the model as follows:

$$GI_{it} = \alpha_0 + \alpha_1 FC_{it} + \alpha_2 ESG_{it} + \alpha_3 Env\_Reg_{it} + \alpha_4 (FC \times ESG)_{it} + \alpha_5 (FC \times Env\_Reg)_{it} + \alpha_6 (ESG \times Env\_Reg)_{it} + \alpha_7 (FC \times ESG \times Env\_Reg)_{it} + \gamma X_{it} + \mu_i + \lambda_t + \nu_{it}$$

where Env_Reg_{it} is the environmental regulation intensity. The coefficient α_7 captures whether regulatory pressure amplifies the moderating effect of ESG performance on the constraint-innovation relationship.

Estimation method

We employed the fixed effects panel regression analysis as our primary estimation method. This method addresses time-invariant unobserved heterogeneity at the industry level that may correlate with both financial constraints and innovation outcomes. Year fixed effects control for macroeconomic shocks and temporal trends affecting all firms simultaneously, such as national innovation policies or global technological developments. Standard errors are clustered at the firm level to account for serial correlation in innovation activities and firm-specific shocks that may affect both financial conditions and patenting behavior over time.

In this study, we implement several robustness strategies to address the potential endogeneity concerns arising from reverse causality (innovative firms may attract better financing) and omitted variable bias. We employ lagged values of financial constraints and ESG performance to mitigate simultaneousness bias. Additionally, we conduct subsample analyses across ownership types, firm sizes, and industry categories to examine heterogeneous effects and validate the generalizability of our findings.

Results

Table 1 shows the empirical evidence supporting our double-edged sword hypothesis. The baseline analysis (Model 1) reveals that financial constraints exert a significant negative effect on green innovation ($\beta = -0.084$), consistent with traditional perspectives that capital limitations impede R&D investments and green innovation. This finding aligns with Zhang and Jin (2021), who demonstrated that financial constraints have an adverse effect on green innovation while R&D expenditure serves as a significant driver. However, the interaction results in Model 2 show a more multifaceted relationship, while the coefficients of the direct effect of financial constraints increase to −0.325, the interaction term (FC*ESG) exhibits a positive and significant coefficient of 0.062, indicating that ESG performance changes the negative influence of financial constraints to a positive effect. The economic significance of this moderation effect is substantial, as for firms with ESG scores above the 65th percentile, financial constraints paradoxically enhance green innovation and support the induced innovation hypothesis under sustainability-oriented governance.

In Model 3, the results for ESG components are shown, and it shows that environmental performance drives the moderation effect most strongly, with the interaction coefficient FC*E (0.048) exceeding those for social and governance dimensions. The above results align with the findings of Gan and Yusupov (2025), who documented that the environmental pillar demonstrates a stronger influence on green innovation than the governance and social pillar. In contrast to Gan and Yusupov (2025), social ranks second, and the governance pillar has the lowest coefficient. The non-linear specification (Model 4) indicates that ESG's innovation-enhancing effect accelerates at higher performance levels (ESG_sq = 0.028), suggesting increasing returns to sustainability investments.

Table 2 shows the role of environmental regulations in shaping the double-edged sword mechanism. The triple interaction model (1)

Table 1
Main Results – The Double-Edged Sword of Green Innovation.

	(1) Base	(2) Interaction	(3) ESG Components	(4) Non-linear
FC	−0.084***	−0.325***	−0.433***	−0.402***
	(0.026)	(0.073)	(0.085)	(0.102)
ESG	0.079***	0.122***		−0.077
	(0.009)	(0.016)		(0.062)
FC*ESG		0.062***		0.076*
		(0.019)		(0.039)
E			0.139***	
			(0.017)	
S			0.021**	
			(0.010)	
G			0.035***	
			(0.011)	
FC*E			0.048**	
			(0.019)	
FC*S			0.013	
			(0.012)	
FC*G			0.038***	
			(0.013)	
FC_sq				−0.011
				(0.040)
ESG_sq				0.028***
				(0.009)
FC*ESG_sq				0.000
				(0.001)
Size	0.423***	0.420***	0.407***	0.416***
	(0.015)	(0.015)	(0.015)	(0.015)
Lev	0.342***	0.352***	0.292***	0.346***
	(0.064)	(0.065)	(0.064)	(0.064)
SOE	0.113***	0.112***	0.118***	0.113***
	(0.030)	(0.030)	(0.029)	(0.030)
Inst_own	−0.077	−0.075	−0.071	−0.077
	(0.047)	(0.047)	(0.047)	(0.047)
Analyst	0.077***	0.077***	0.079***	0.077***
	(0.016)	(0.016)	(0.016)	(0.016)
TobinQ	0.009**	0.010**	0.009**	0.009**
	(0.004)	(0.004)	(0.004)	(0.004)
Indep	0.159	0.158	0.232	0.126
	(0.203)	(0.203)	(0.200)	(0.203)
Fixed	−0.535***	−0.539***	−0.559***	−0.538***
	(0.086)	(0.086)	(0.086)	(0.086)
_cons	−9.073***	−9.184***	−8.952***	−8.749***
	(0.336)	(0.338)	(0.336)	(0.335)
Adj. R^2	0.360	0.360	0.366	0.361

Note: Asterisks denote statistical significance at the 10 %, 5 %, and 1 % levels (*, **, ***).

reveals that the coefficient on FC × ESG × Regulation (0.070) is positive and significant, indicating that regulatory pressure amplifies ESG's moderating effect. These findings support the Porter Hypothesis by demonstrating that regulations not only stimulate innovation directly but also enhance firms' ability to transform constraints into innovation catalysts (Porter & Van Der Linde, 1995).

Table 2
Moderating Role of Environmental Regulations.

	(1) Triple Interaction	(2) Continuous	(3) High Regulation	(4) Low Regulation
FC	−0.292***	−0.272**	−0.381***	−0.290***
	(0.094)	(0.114)	(0.101)	(0.093)
ESG	0.092***	0.077***	0.143***	0.109***
	(0.022)	(0.027)	(0.022)	(0.022)
high_env_reg	−0.336***			
	(0.113)			
Env_reg		−0.438***		
		(0.099)		
FC*ESG	0.029	0.013	0.091***	0.037
	(0.025)	(0.030)	(0.027)	(0.025)
Env_reg*FC	−0.092			
	(0.129)			
Env_reg *ESG	0.066**			
	(0.031)			
Env_reg*FC*ESG	0.070**			
	(0.035)			
Adj. R^2	0.364	0.365	0.377	0.355

Note: Asterisks denote statistical significance at the 10 %, 5 %, and 1 % levels (*, **, ***).

The subsample analysis provides compelling evidence for regulatory heterogeneity. Under high environmental regulation (Model 3), the FC × ESG interaction coefficient increases to 0.091, compared to an insignificant 0.037 in low-regulation environments. The high difference in coefficients highlights the importance of stringent regulations. The mechanism operates through regulatory-induced market demand for green technologies and preferential access to government support, as documented by Shi and Zhou (2024), who demonstrated that government R&D subsidies combined with strengthened environmental regulation create synergistic effects that amplify green innovation impacts through financing constraints and cost mechanisms.

Table 3 reveals substantial heterogeneity in the double-edged sword effect across firm types. State-owned enterprises exhibit stronger ESG moderation effects (FC*ESG = 0.074) compared to private firms (0.039). The effect also varies by firm size and industry characteristics. Large firms show marginally weaker moderation effects than small firms, suggesting that resource-constrained smaller enterprises may benefit more from ESG-driven efficiency gains. In particular, the heavily polluting industries show the strongest interaction effect (0.094), indicating that environmental pressures and stakeholder scrutiny in these sectors amplify the transformation of constraints into innovation drivers. These patterns support heterogeneous treatment effects shown by Liu et al. (2022), who demonstrated that digital finance's impact on green innovation is more pronounced in high-polluting industries, where environmental pressures create stronger incentives for technological transformation.

Table 4 shows the robustness analysis and confirms our findings across alternative methodologies and variable constructions. Using an alternative financial constraint measure based on credit ratings (Model 2), the interaction effect remains significant with a coefficient of 0.024. The Poisson specification (Model 3) addresses concerns about the count nature of patent data, with results qualitatively similar to our main findings. The green patent ratio specification (Model 4) demonstrates that effects persist when scaling innovation by total patent output, ruling out mechanical relationships driven by overall innovation capacity.

Table 3
Heterogeneity Analysis.

	(1) SOE	(2) Private	(3) Large	(4) Small	(5) Polluting	(6) Clean
FC	−0.329**	−0.257***	−0.384***	−0.201***	−0.357***	−0.327***
	(0.140)	(0.079)	(0.112)	(0.069)	(0.135)	(0.086)
ESG	0.149***	0.097***	0.149***	0.076***	0.139***	0.118***
	(0.028)	(0.019)	(0.022)	(0.016)	(0.030)	(0.020)
FC*ESG	0.074**	0.039*	0.055**	0.041**	0.094**	0.053**
	(0.036)	(0.021)	(0.028)	(0.018)	(0.038)	(0.022)
Size	0.479***	0.366***	0.551***	0.242***	0.401***	0.431***
	(0.027)	(0.018)	(0.027)	(0.016)	(0.028)	(0.018)
Lev	0.034	0.543***	0.466***	0.344***	0.072	0.415***
	(0.127)	(0.070)	(0.114)	(0.057)	(0.118)	(0.076)
SOE	0.000	0.000	0.122***	0.053*	0.121**	0.101***
	(.)	(.)	(0.042)	(0.028)	(0.048)	(0.035)
Inst_own	0.010	−0.131***	−0.078	−0.105**	−0.075	−0.063
	(0.125)	(0.050)	(0.081)	(0.044)	(0.076)	(0.057)
Analyst	0.039	0.099***	0.086***	0.093***	−0.004	0.097***
	(0.038)	(0.017)	(0.024)	(0.014)	(0.027)	(0.019)
TobinQ	0.027**	0.006*	−0.011	−0.000	0.012**	0.010*
	(0.013)	(0.003)	(0.015)	(0.001)	(0.005)	(0.005)
Indep	0.473	−0.183	0.243	−0.148	−0.392	0.336
	(0.371)	(0.222)	(0.310)	(0.195)	(0.310)	(0.241)
Fixed	−0.628***	−0.404***	−0.594***	−0.544***	0.245*	−0.820***
	(0.136)	(0.103)	(0.128)	(0.075)	(0.140)	(0.106)
Adj. R^2	0.448	0.294	0.396	0.147	0.344	0.370

Note: Asterisks denote statistical significance at the 10 %, 5 %, and 1 % levels (*, **, ***).

Table 4
Robustness Tests (Composite Index and Alternatives).

	(1) Composite FC	(2) Alternative FC (CR)	(3) Poisson (Patent Count)	(4) Patent Ratio
FC	−0.325***		−0.261***	−0.073***
	(0.073)		(0.080)	(0.027)
ESG	0.122***	0.098***	0.100***	0.031***
	(0.016)	(0.009)	(0.015)	(0.006)
FC*ESG	0.062***		0.025	0.006
	(0.019)		(0.018)	(0.006)
FC*ESG_CR		0.024**		
		(0.009)		
Adj. R^2	0.360	0.374		0.238

Note: Asterisks denote statistical significance at the 10 %, 5 %, and 1 % levels (*, **, ***).

Table 5 gives the results for temporal dynamics and potential reverse causality. The lagged specification (Model 1) shows that prior-period financial constraints and ESG performance show similar interaction effects (L.FC*ESG = 0.056), mitigating concerns about contemporaneous feedback effects. The persistence model (Model 2) reveals that controlling for past innovation performance reduces but does not eliminate the interaction effect, suggesting our results capture more than path-dependent innovation trajectories. The future effects model (Model 3) provides particularly compelling evidence for causality. The current financial constraints and ESG performance predict green innovation two years in advance (FC*ESG = 0.065), with magnitudes comparable to coexistent effects.

Conclusions

The present study examines the relationships between financial constraints, ESG performance, and green innovation by proposing a "double-edged sword" hypothesis. Using panel data for firms operating in Shanghai and Shenzhen stock exchanges of China from 2010 to 2023, our results showed that the negative relationship between financial constraints and innovation can be transformed to a positive relationship through strong ESG performance. Our findings reveal that while financial constraints have an adverse effect on green innovation, this effect reverses for firms with ESG scores above the 65th percentile, where resource limitations paradoxically enhance innovation. The mechanisms underlying this transformation operate through enhanced resource utilization efficiency, superior stakeholder relationships, and alignment between sustainability objectives and innovation strategies. Additionally, the results for environmental regulations included as the triple interaction variable along with financial constraints, ESG performance have the strongest effect on green innovation. This suggests that the Porter Hypothesis operates not merely through direct regulatory pressure but also by creating contexts where sustainability-oriented firms can leverage resource constraints as an innovation driver. The results of heterogeneity analysis reveal that state-owned enterprises, heavily polluting industries, and smaller firms show stronger transformation effects. These patterns reflect differential capabilities in converting ESG investments into tangible innovation outcomes under resource constraints. As a robustness analysis, we employed alternative specifications, variable constructions, and dynamic models, which further confirm our findings.

The findings of this study offer several theoretical contributions to the literature. First, we further expand the innovation hypothesis by identifying organizational conditions, specifically ESG performance, that enable firms to transform constraints into innovation drivers. This

Table 5
Dynamic Analysis (Composite Index).

	(1) Lagged	(2) Persistence	(3) Future Effect
L.FC	−0.294***		
	(0.075)		
FC		−0.134***	−0.389***
		(0.035)	(0.081)
L.ESG	0.115***		
	(0.017)		
ESG		0.046***	0.132***
		(0.007)	(0.018)
L.FC*ESG	0.056***		
	(0.020)		
FC*ESG		0.024***	0.065***
		(0.009)	(0.021)
L.GI		0.725***	
		(0.007)	
Size	0.435***	0.122***	0.432***
	(0.016)	(0.005)	(0.017)
Lev	0.308***	0.105***	0.300***
	(0.065)	(0.024)	(0.074)
SOE	0.125***	0.035***	0.106***
	(0.031)	(0.010)	(0.033)
Inst_own	−0.086*	−0.002	−0.023
	(0.052)	(0.017)	(0.054)
Analyst	0.080***	0.031***	0.096***
	(0.017)	(0.006)	(0.019)
TobinQ	0.010**	0.002**	0.015***
	(0.004)	(0.001)	(0.005)
Indep	0.177	0.058	0.157
	(0.213)	(0.073)	(0.234)
Fixed	−0.555***	−0.166***	−0.536***
	(0.091)	(0.029)	(0.096)
Adj. R^2	0.363	0.694	0.349

Note: Asterisks denote statistical significance at the 10 %, 5 %, and 1 % levels (*, **, ***).

challenges the traditional view that financial constraints have an adverse effect on green innovation and suggests that resource scarcity's impact depends on firms' ESG performance and stakeholder management capabilities. Second, our findings add to the ESG literature by showing that sustainability practices generate value not only through traditional channels like cost reduction and risk mitigation but also by fundamentally changing how firms respond to adversity. High ESG performance emerges as a dynamic capability that enables adaptive responses to resource constraints, suggesting that sustainability investments create option value that is particularly valuable during financial stress. Third, we contribute to institutional theory by revealing the role of environmental regulations in interacting with firm-level capabilities to shape innovation outcomes. The positive effect of regulations on the ESG-constraint interaction indicates that institutional pressures and organizational resources operate as complements rather than substitutes in driving innovation.

For corporate managers, our results highlight the strategic value of ESG investments beyond reputational benefits. Based on the results of this study, we argue that ESG capabilities serve as insurance against financial constraints, enabling firms to maintain or even accelerate innovation during capital market frictions. The differential effects across ESG dimensions suggest prioritizing environmental initiatives for innovation outcomes while maintaining balanced attention to social and governance factors for their complementary effects. Policymakers should reconsider the approach of one policy for all to either ease financial constraints or tighten environmental regulations. Our results suggest that moderate financial pressure combined with stringent environmental standards and support for ESG capability development may optimize green innovation. The heterogeneous effects across firm types indicate that targeted policies considering ownership structure, industry characteristics, and firm size could enhance effectiveness. For investors, the transformation of financial constraints from innovation barriers to drivers among high-ESG firms suggests reconsidering risk assessments and valuation models. Firms combining strong ESG performance with moderate financial constraints may represent overlooked innovation opportunities, particularly in heavily regulated industries where the triple interaction effects are strongest.

CRediT authorship contribution statement

Lihui Yu: Writing – review & editing, Writing – original draft, Software, Formal analysis, Data curation, Conceptualization. **Pengwei Jin:** Writing – review & editing, Validation, Supervision, Software, Resources, Investigation.

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. The authors report there are no competing interests to declare.

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