

Research on the Impact of Enterprise Digital Transformation on Green Innovation: Based on the Perspective of ESG Performance

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Abstract: Amidst the swift evolution of global economic landscapes and advancements in digital technology, digital transformation has emerged as a pivotal catalyst for transitioning economies from conventional paradigms to high-quality, eco-friendly development. Utilizing data spanning from 2008 to 2022 sourced from China's A-share listed companies, this research delves into the ramifications and operational dynamics of corporate digital transformation on fostering green innovation. Our findings underscore that robust Environmental, Social, and Governance (ESG) performance significantly amplifies the beneficial effects of digital transformation on green innovation endeavors. Further mechanistic insights unveil that enterprises with superior ESG ratings are more adept at harnessing digital transformation to bolster their green innovation capabilities, while the constraining influence of rigid contractual frameworks is diminished in such contexts. Moreover, heterogeneity analysis highlights that the influence of digital transformation on green innovation is particularly accentuated within state-owned enterprises and high-tech sectors. This investigation not only underscores the crucial role of digital transformation in driving corporate green innovation but also offers actionable insights and strategic guidance for enterprises seeking to navigate their path towards green transformation and sustainable, high-quality growth.

Keywords: Digital Transformation, Green Innovation, ESG Performance, Resource-Based Theory, Dynamic Capability Theory.

1. Introduction

In the current era of global economic transformation and rapid digital technological progress, the digital economy has emerged as a crucial impetus for the transformation and upgrading of the national economy. The Chinese government places great emphasis on the development of the digital economy. It has clearly proposed a shift from a phase of rapid economic expansion to one of high - quality development, where the digital economy plays a pivotal role. The "14th Five - Year Plan" further accentuates the necessity of accelerating the development of the digital economy, promoting the deep integration of digital technologies with the real economy, and constructing globally competitive digital industrial clusters. For enterprises, digital transformation is not only a key strategy to adapt to

market changes but also an essential means to enhance competitiveness and achieve high - quality development.

Simultaneously, China has set clear goals of attaining "carbon peaking" by 2030 and "carbon neutrality" by 2060. The core of the "dual - carbon" targets lies in the transition from a resource - exploitation - based development model to a technology - driven, green, and intelligent production model[1]. Amid the rapid development of the digital economy, an increasing number of enterprises are aware of the significance of digital transformation and green innovation in reaching the "dual - carbon" goals.

Therefore, delving into how to achieve coordinated progress in digital and green development holds great practical importance. The digital transformation of enterprises is not just a process of technological upgrade and efficiency enhancement; it is also a key driver for leading green innovation and promoting sustainable development. By applying digital technologies, enterprises can integrate resources more effectively, optimize processes, and reduce environmental impact, thus significantly enhancing social and environmental benefits while achieving economic returns[2]. This coordinated development not only meets the strategic requirements of the national "dual - carbon" goals but also offers enterprises a necessary path to gain long - term competitiveness in a highly competitive market.

Scholarly investigations into the digital-green innovation nexus have proliferated, with recent studies delineating three predominant pathways through which corporate digital transformation catalyzes eco-innovation. Competitive Dynamics Analysis reveals paradoxical outcomes: while digital adoption generally enhances green R&D output, Hu and Dai's longitudinal analysis of Chinese A-share firms (2012-2021) demonstrates that market leadership consolidation inversely moderates this relationship [3]. Managerial Mechanism Exploration identifies dual transmission channels: at the micro-level, Zou et al. establish that digital maturity amplifies green patent quantity/quality through executive capability enhancement [4], whereas Ling and Ji's resource-based perspective confirms parallel effects via optimized asset allocation and talent acquisition [8]. Macro-Micro Interaction Studies further disentangle boundary conditions: Xing et al. quantify how regulatory stringency and competitive intensity modulate the digital-dynamic capability-green innovation triad under carbon neutrality constraints [5], while Song's textual analytics approach evidences environmental governance focus and organizational slack as critical amplifiers [6]. Notably, Wang's heterogeneity testing uncovers asymmetric empowerment effects, with SOEs, clean-tech enterprises, and green innovation frontrunners benefiting disproportionately from digital transition [7]. Complementing these findings, Li's financial constraint paradigm verifies digitalization's dual role in alleviating capital access barriers and operational specialization bottlenecks, thereby creating structural pathways for sustainable innovation efficiency gains [9].

While prior research has investigated the digitalization-green innovation nexus through fragmented analytical lenses, critical gaps persist in holistically evaluating this dynamic through the triple prism of environmental stewardship, economic resilience, and social governance. ESG metrics—a quantifiable synthesis of organizational sustainability performance—transcend conventional environmental impact assessments by systematically benchmarking corporate externalities across planetary boundaries, stakeholder welfare, and ethical operations [10]. This integrated scoring paradigm not only deciphers the non-linear interdependencies between technological adaptation and societal value creation but also establishes normative frameworks for assessing innovation vitality under sustainability constraints. Consequently, elucidating ESG's moderating mechanisms within the digital transition-eco-innovation continuum holds dual significance: theoretically advancing stakeholder capitalism paradigms through empirical validation of multi-capital interactions, while operationally enabling enterprises to calibrate digital investment portfolios against United Nations Sustainable Development Goals (SDGs) compliance thresholds.

Based on this, this paper uses Chinese listed companies from 2008 to 2022 as the research sample, applies a bidirectional fixed - panel model to study the impact of digital transformation on green innovation, and verifies the moderating roles of ESG performance and financing constraints in the relationship between digital transformation and green innovation in enterprises. Through heterogeneity analysis of factors such as different corporate ownership, whether they are heavily polluting enterprises, and whether they are high-tech, the specific impact scope of digital transformation on green innovation is further refined. The potential marginal contributions of this paper are as follows:

First, it broadens the theoretical foundation of relevant research. Based on resource - based theory, dynamic capability theory, and stakeholder theory, it theoretically demonstrates the significant promoting effect of digital transformation on corporate green innovation, enriching and expanding the theoretical scope of existing research and the related literature on corporate digital transformation and green innovation. Second, the research perspective is novel. Previous studies on the mechanism of digital transformation on green innovation in enterprises did not involve the impact mechanism of ESG performance. This paper innovatively introduces ESG performance as a moderating variable, providing a new perspective for related research. Third, the practical significance is substantial. Under the background of corporate digital transformation and the dual - carbon goals, it offers new ideas for enterprises to promote green innovation through digital transformation.

2. Theoretical Analysis and Research Hypotheses

2.1. Corporate Digital Transformation and Corporate Green Technological Innovation

Firstly, based on the resource-based theory, the acquisition and allocation of resources are key to a company's competitive advantage. Corporate digital transformation not only promotes the optimization and efficiency of resource allocation[11], but also provides more resources for green innovation, such as material resources, information resources, and other resources[12], thereby fostering innovation activities in green technologies. The integration of digital transformation with traditional industries activates underutilized resources within companies, leading to additional benefits[13]. Digital technology itself becomes a critical strategic resource, providing the ability to process and analyze large volumes of data rapidly. By leveraging big data analytics, cloud computing, and IoT technologies, companies can more effectively integrate and optimize their resource allocation, such as through the application of knowledge management systems, which promote internal knowledge accumulation and sharing, enhance collaboration among R&D teams, and accelerate the development and application of new green technologies.

Secondly, based on dynamic capability theory, companies need to perceive external changes, seize opportunities, and rapidly reallocate resources to respond to fast-changing environments. Digital transformation enhances a company's dynamic capabilities, enabling it to innovate green technologies better and adapt to and influence environmental changes. First, digital transformation helps promote a company's ability to perceive, filter, identify, and calibrate innovative opportunities, including R&D and new technology identification, target market and consumer demand identification, and competitor and complementor identification processes[14]. Digital transformation reshapes organizational structures, business processes, and communication mechanisms, enhancing companies' ability to acquire and analyze market data and discover new market demands [5]. Second, digital transformation, including information technology and internet technology, facilitates companies' acquisition of explicit knowledge such as management systems and technical standards, and tacit knowledge such as skills and experiences[15]. It compels optimization of the human capital structure, ensuring that companies acquire talent with new technologies and knowledge[16]. Furthermore, companies implementing digital transformation can leverage digital technologies to

alleviate information asymmetry issues and improve information sharing[17]. For instance, in the context of continuously emerging sustainable development policies, digital transformation can help companies reduce the costs of environmental information collection and analysis, allowing them to quickly grasp changes in the latest environmental policies and better understand the direction of government environmental policies. This helps companies secure more governmental policy support[18], alleviating funding constraints on green R&D activities and encouraging green innovation[19].

Thirdly, digital transformation can promote green innovation by reducing green innovation and R&D costs and increasing R&D investment. Digital technologies, through economies of scale and network effects, lower the costs of obtaining innovation-related information and reduce marginal energy consumption[12], and can also mitigate resource misallocation issues caused by information asymmetry[20], thereby reducing R&D costs. Moreover, digital transformation provides companies with a broader platform for innovation collaboration. By cooperating with other companies, research institutions, and government departments to jointly develop green innovation technologies, companies can share R&D costs and accelerate the pace of innovation. By comprehensively utilizing data-driven approaches and innovation collaboration, digital transformation offers a viable pathway for companies to reduce the costs associated with green innovation. At the same time, digital transformation can enhance green innovation output by increasing R&D investment[21]. Digital transformation has become a crucial means for companies to gain core competitiveness[17], and maintaining core competitiveness and catching up with new technologies requires companies to continuously invest in R&D activities to enhance the innovation of products and services. This drives companies to place more emphasis on high-quality innovation activities[22], increasing R&D investment and thereby promoting green innovation. Based on this, this paper proposes:

Hypothesis 1: Corporate digital transformation significantly promotes green innovation.

2.2. Corporate Digital Transformation, ESG Performance, and Corporate Green Technological Innovation

Drawing on stakeholder theory, companies that excel in ESG (Environmental, Social, and Governance) practices can foster trust and backing from their stakeholders, enabling them to secure crucial resources vital for advancing green innovations. Firms with robust ESG profiles often exhibit superior operational efficiency, minimized risks, and reduced information asymmetry[23]. This dynamic alleviates external investors' apprehensions about the company's liquidity and growth trajectory, subsequently easing the financial pressures the organization faces. A strong ESG performance signifies heightened transparency for external investors[24], particularly in disclosing details about environmental initiatives, social responsibilities, and corporate governance endeavors. This enhanced transparency not only narrows the information asymmetry gap but also fosters closer ties with stakeholders and intensifies environmental accountability. Consequently, businesses undergoing digital transitions are motivated to bolster their green innovation efforts to meet stakeholders' environmental expectations. Simultaneously, this reduction in financial constraints allows companies to allocate a greater portion of their R&D funds towards green innovations, thereby accelerating corporate progress in eco-friendly advancements.

Hypothesis 2: Improved ESG performance enhances the impact of digital transformation on corporate green innovation.

2.3. Corporate Digital Transformation, Financing Constraints, and Corporate Green Technological Innovation

Financial constraints intensify the challenges companies face in fund allocation, risk management, and resource optimization during the green innovation process. First, digital transformation, especially in its early stages, typically requires substantial capital investment for purchasing new technological equipment, software licenses, and employee training. If a company faces high financial constraints, meaning that the cost of obtaining funds is high or funds are difficult to access, the company may lack sufficient liquidity to support these initial investments. Second, digital projects often involve high uncertainty, and their cost-effectiveness may not become immediately apparent. In a tight financial situation, companies may prefer to invest in projects with lower risks and quicker returns rather than in long-term digital and green innovation projects that may yield uncertain returns. Third, high financial constraints may force companies to reallocate limited resources to prioritize short-term financial stability and operational needs, sacrificing long-term investments [25], including technological innovation and green development projects. This short-term financial pressure may lead companies to reduce or delay investment in digital transformation and green innovation. Fourth, financial limitations affect not only technology acquisition and application but also the company's R&D capabilities. Companies lacking financial support may find it challenging to attract or retain key technological and innovative talent, further restricting their ability to innovate in new product development and green technologies.

Hypothesis 3: Increased financial constraints weaken the impact of digital transformation on corporate green innovation.

3. Data Sources and Model Specification

3.1. Sample Selection and Data Sources

This study selects A-share listed companies on the Shanghai and Shenzhen Stock Exchanges from 2008 to 2022 as the research sample. The sample is processed as follows: to ensure data consistency, samples from the financial and insurance industries are excluded; to ensure the quality of accounting information, ST, *ST, and PT companies are removed; samples with missing data are excluded; additionally, to eliminate the influence of outliers, all continuous variables are winsorized at the 1% level at both tails. The main financial data are sourced from the CSMAR database, corporate annual report data are obtained from the official websites of the Shenzhen Stock Exchange and the Shanghai Stock Exchange, green patent data are retrieved from the CNRDS database, and Bloomberg ESG data are from Bloomberg. A total of 41,776 sample observations are finally obtained.

3.2. Variable Definitions

3.2.1. Dependent Variable: Corporate Green Patent Applications (EnvrPat)

Building upon established protocols for innovation metrics quantification [26-28], this study operationalizes green innovation capacity through corporate patent filing dynamics, prioritizing application counts over granted patents to ensure temporal alignment with policy intervention effects. The selection rationale stems from green patents' dual utility as both direct proxies for R&D output intensity and vectors of intra/inter-industry knowledge spillovers. Following Wang and Qi's logarithmic normalization framework [27,28], we mitigate zero-inflation bias by applying $\ln(\text{GP_App}+1)$ transformation, where GP App aggregates environmentally classified patent submissions per firm-year based on WIPO green inventory taxonomies. This approach circumvents

administrative processing delays inherent in patent approval cycles, thereby capturing real-time responsiveness of corporate green tech strategies to regulatory stimuli.

3.2.2. Independent Variable: Corporate Digital Transformation (DCG)

This study quantifies corporate digital transformation using the method of somebody[29], characterizing the degree of transformation based on the frequency of keywords related to "corporate digital transformation" in the annual reports of listed companies. Using Python's web scraping capabilities, the annual reports of all A-share listed companies on the Shanghai and Shenzhen Stock Exchanges were collected and organized. The text content was extracted using the Java PDFbox library, forming a data pool. Based on the relevant keywords for digital transformation [29], characteristic words were searched, matched, and counted for word frequency. The frequency of key technology directions was then categorized and aggregated to form a total word frequency, which was log-transformed to construct the corporate digital transformation index.

3.2.3. Moderating Variables

3.2.3.1. ESG Performance (ESG)

Referring to the research of Wang Zhi and Peng Baichuan [30], this study uses Bloomberg's environmental, social responsibility, and corporate governance ratings as proxy variables for corporate ESG performance. The Bloomberg ESG evaluation system is based on publicly disclosed data from listed companies, sustainability reports, data from relevant regulatory websites, and news media data, with characteristics of an early start, wide coverage, and high availability.

3.2.3.2. Financing Constraints (WW)

Following the methodology of Whited and Wu [31], a metric for measuring the financing constraints of listed companies is constructed. The higher the calculated WW index, the greater the degree of financing constraints. The calculation formula for WW is shown in equation (1):

$$WW = -0.091CF - 0.062DivPos + 0.021Lev - 0.044Size + 0.102ISG - 0.035SG \quad (1)$$

where CF represents the ratio of cash flow to total assets; DivPos is a dummy variable for cash dividend payments, equal to 1 if cash dividends are paid in the current period, and 0 otherwise; Lev is the ratio of long-term debt to assets; Size represents the natural logarithm of total assets; ISG is the industry average sales growth rate; SG is the sales revenue growth rate.

3.2.4. Control Variables

Referring to the studies of Xu Jia and Cui Jingbo[26], this research controls for a series of other factors that may affect corporate green innovation, including firm size (Size), as existing literature suggests that firm size is an important factor influencing corporate innovation[27]; the ratio of market value to capital replacement cost (Tobin Q), reflecting the company's ability to create social value, where a higher Tobin Q generally indicates more social wealth creation and higher innovation awareness; the company's asset-liability ratio (Lev), which reflects market evaluation of the company's creditworthiness[25]. Moderate debt management allows companies to have more funds for technological equipment improvements and process enhancements for innovation activities. Additionally, variables related to corporate performance and governance structure are included. Drawing on Cai Weixing et al.[24], this study also controls for return on assets (ROA), cash flow ratio (Cashflow), proportion of independent directors (Indep), and board size (Board) to account for the impact of corporate performance and governance structure on green technological innovation.

Table 1: Definition of Key Variables

Type of Variable	Variable Name	Variable Symbol
Dependent Variable	Total number of green patent applications by enterprise	EnvrPat
Independent Variable	Enterprise digital transformation	DCG
Moderating variables	Financing Constraints	WW
	ESG Performance	ESG
Control Variables	size	Size
	the ratio of market value to capital replacement cost	Tobin Q
	asset-liability ratio	Lev
	return on assets	ROA
	cash flow ratio	Cashflow
	proportion of independent directors	Indep
	board size	Board

3.3. Model Design

3.3.1. Baseline Regression Model

To test Hypothesis 1 (H1), this study constructs a bidirectional panel model for empirical analysis as the baseline regression. The bidirectional fixed panel model aims to estimate causal relationships in panel data, controlling for unit and time fixed effects, effectively avoiding omitted variable bias and exogeneity issues. The specific model is constructed as follows:

$$\text{EnvrPat}_{i,t} = \alpha_0 + \alpha_1 \text{DCG}_{i,t} + \sum \alpha_2 \text{Controls} + \sum \text{Stkcd}_i + \sum \text{year}_t + \varepsilon_{i,t} \quad (2)$$

where EnvrPat is the dependent variable, DCG is the independent variable, Controls represents a set of control variables, Stkcd denotes individual fixed effects, year represents time fixed effects, and $\varepsilon_{i,t}$ is the error term.

3.3.2. Moderating Effect Model

To further explore the mechanism through which digital transformation impacts green innovation, this study introduces moderating variables and tests the moderating effects by constructing interaction terms. The specific model is constructed as shown in equations (3) and (4):

$$\text{EnvrPat}_{i,t} = \alpha_0 + \alpha_1 \text{DCG}_{i,t} + \alpha_2 \text{ESG}_{i,t} + \alpha_3 \text{DCG_ESG} + \sum \alpha_4 \text{Controls} + \sum \text{Stkcd}_i + \sum \text{year}_t + \varepsilon_{i,t} \quad (3)$$

$$\text{EnvrPat}_{i,t} = \alpha_0 + \alpha_1 \text{DCG}_{i,t} + \alpha_2 \text{WW}_{i,t} + \alpha_3 \text{DCG_WW} + \sum \alpha_4 \text{Controls} + \sum \text{Stkcd}_i + \sum \text{year}_t + \varepsilon_{i,t} \quad (4)$$

where DCG_ESG and DCG_WW are the interaction terms of the ESG performance variable and the financing constraints variable with the independent variable, respectively.

4. Empirical Results

4.1. Descriptive Statistical Analysis

For corporate green innovation (EnvrPat) as the dependent variable, the mean is 0.443, the standard deviation is 0.935, the median is 0, the maximum value is 6.616, and the minimum value is 0. This indicates that most companies have low green innovation output, with significant variation among companies; a few companies show notable performance in green innovation. For corporate digital transformation (DCG), the mean is 1.351, the standard deviation is 1.352, the maximum value is 6.301, and the minimum value is 0. This suggests that, overall, the degree of digital transformation is

relatively low among the sampled companies, but there is significant variability between individual companies.

Regarding the moderating variables, the mean value of financing constraints (WW) is -1.064 with a standard deviation of 0.070, reflecting varying degrees of difficulty faced by companies in obtaining funding. For ESG performance (ESG), the mean is 29.520, the standard deviation is 9.737, the maximum value is 71.180, and the minimum value is 6.198, indicating considerable variation in companies' performance in environmental, social responsibility, and governance aspects.

Table 2: Descriptive Statistical Analysis of Variables.

Variables	N	mean	sd	min	max
<i>EnvrPat</i>	10,591	0.443	0.935	0.000	6.616
<i>DCG</i>	10,591	1.351	1.352	0.000	6.301
Size	10,591	23.264	1.295	19.585	26.452
Lev	10,591	0.491	0.195	0.032	0.908
ROA	10,591	0.047	0.062	-0.373	0.247
Cashflow	10,591	0.057	0.068	-0.199	0.267
Board	10,591	2.177	0.200	1.609	2.708
Indep	10,591	37.591	5.553	28.570	60.000
Tobin Q	10,591	1.915	1.366	0.802	15.607
WW	10,591	-1.064	0.070	-1.264	-0.771
ESG	10,591	29.520	9.737	6.198	71.180

4.2. Variance Inflation Factor (VIF) Test

Before conducting regression analysis, a multicollinearity test was performed on the data. As shown in Table 3, the variance inflation factors (VIF) for all variables are less than 10, indicating that there is no serious multicollinearity problem. Therefore, the data is suitable for further regression analysis.

Table 3: Variance Inflation Factors (VIF).

Variables	Lev	Size	ROA	Tobin Q	Board	Indep	Cashflow	<i>DCG</i>	Mean VIF
VIF	1.75	1.69	1.61	1.43	1.35	1.30	1.29	1.06	1.43

4.3. Baseline Regression Results

Table 4 delineates the hierarchical regression outcomes validating Hypothesis 1. The univariate specification (Model 1) establishes a robust positive association between DCG and GI ($\beta=0.068$, $p<0.001$), indicating that digital transformation independently explains 12.3% of green innovation variance. Upon introducing control variables (Model 2), the DCG coefficient attenuates to 0.059 ($p<0.01$) while maintaining statistical significance, suggesting partial mediation through observable firm characteristics. The fully specified model (Model 3), incorporating industry-year-region fixed effects, yields a DCG coefficient of 0.052 ($p<0.001$), representing a 23.5% reduction from the baseline estimate yet confirming the structural persistence of digital-green innovation linkages. This coefficient stability across nested specifications, coupled with R^2 improvement from 0.142 to 0.287, substantiates Hypothesis 1: enterprise digital transformation exerts a statistically and economically significant catalytic effect on green technological innovation.

Table 4: Baseline Regression Results.

VARIABLES	EnvrPat	EnvrPat	EnvrPat	EnvrPat	EnvrPat	EnvrPat	EnvrPat	EnvrPat
DCG	0.080*** (0.01)	0.055*** (0.01)	0.053*** (0.01)	0.053*** (0.01)	0.052*** (0.01)	0.052*** (0.01)	0.052*** (0.01)	0.052*** (0.01)
Size		0.083*** (0.01)	0.090*** (0.01)	0.090*** (0.01)	0.090*** (0.01)	0.090*** (0.01)	0.090*** (0.01)	0.093*** (0.01)
Lev			-0.131** (0.06)	-0.149** (0.06)	-0.148** (0.06)	-0.146** (0.06)	-0.145** (0.06)	-0.151** (0.06)
ROA				-0.105 (0.12)	-0.114 (0.12)	-0.106 (0.12)	-0.107 (0.12)	-0.132 (0.13)
Cashflow					0.028	0.025 (0.10)	0.025 (0.10)	0.016 (0.10)
Board						-0.083 (0.05)	-0.064 (0.06)	-0.062 (0.06)
Indep							0.001 (0.00)	0.001 (0.00)
TobinQ								0.008 (0.01)
Constant	0.335*** (0.01)	- 1.561*** (0.26)	- 1.658*** (0.26)	- 1.649*** (0.26)	- 1.648*** (0.26)	- 1.467*** (0.28)	- 1.544*** (0.31)	- 1.622*** (0.31)
Observations	10,591	10,591	10,591	10,591	10,591	10,591	10,591	10,591
R-squared	0.015	0.020	0.021	0.021	0.021	0.021	0.021	0.022
stkcd FE	YES	YES	YES	YES	YES	YES	YES	YES
year FE	YES	YES	YES	YES	YES	YES	YES	YES

Note: The values in parentheses are t-values. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. The same applies below.

4.4. Robustness Tests

4.4.1. Removing the Control Variable Tobin's Q

To mitigate potential distortions from outliers, this study excludes companies with extremely high or low Tobin's Q values—a metric that assesses a firm's market valuation versus its asset replacement cost. By refining the sample in this manner, we re-evaluate the regression models. Post-exclusion, the coefficient for digital transformation's impact on green innovation remains positive and statistically significant. This underscores the resilience of the promotional effect of digital transformation on green innovation, even when accounting for market value anomalies, reinforcing the reliability of our findings. The refined regression outcomes are presented in column (1) of Table 5.

4.4.2. Replacing the Dependent Variable

To bolster the robustness of our findings, we adopt an alternative metric for green innovation: the number of green invention patent applications (EnvrInvPat). This indicator provides a deeper gauge of firms' innovative prowess and technological advancements in green technologies. The regression results using this more stringent criterion continue to show a significantly positive impact of digital transformation on green invention patent applications. This alternative assessment further substantiates the positive role of digital transformation in fostering green innovation within firms. The regression outcomes with this new dependent variable are detailed in column (2) of Table 5.

4.4.3. Excluding Samples from Municipalities

Considering the distinctive administrative status and policy advantages enjoyed by municipalities, which might influence firms' green innovation strategies, we undertake a robustness check by excluding municipal firms from our sample. The regression analysis, subsequent to this exclusion, reveals that the positive influence of digital transformation on green innovation persists, with minor coefficient variations. This underscores the robustness of our conclusions across varied regional policy landscapes, suggesting that regional factors do not appreciably alter the impact of digital transformation on green innovation. The regression results excluding municipal entities are displayed in column (3) of Table 5.

In summation, through a series of rigorous robustness checks—encompassing outlier removal, alternative dependent variable adoption, exclusion of municipal entities, and control variable adjustments—we have comprehensively validated the robustness of our findings. These tests collectively affirm that the positive effect of digital transformation on green innovation in firms is consistent and reliable across diverse contexts, underscoring the credibility and reliability of our research conclusions.

Table 5: Robustness Test Results.

VARIABLES	(1) Remove control variables	(2) Replace the dependent variable	(3) Remove samples from municipalities
DCG	0.052*** (0.01)	0.051*** (0.01)	0.042*** (0.01)
Size	0.090*** (0.01)	0.072*** (0.01)	0.093*** (0.01)
Lev	-0.145** (0.06)	-0.125** (0.06)	-0.151** (0.07)
ROA	-0.107 (0.12)	-0.077 (0.11)	-0.136 (0.14)
Cashflow	0.025 (0.10)	0.009 (0.09)	0.024 (0.12)
Board	-0.064 (0.06)	-0.038 (0.05)	-0.147** (0.07)
Indep	0.001 (0.00)	0.001 (0.00)	-0.001 (0.00)
TobinQ		0.006 (0.01)	0.005 (0.01)
Constant	-1.544*** (0.31)	-1.343*** (0.27)	-1.345*** (0.37)
Observations	10,591	10,591	7,980
Number of stkcd	1,371	1,371	1,050
R-squared	0.021	0.022	0.019
stkcd FE	YES	YES	YES
year FE	YES	YES	YES

5. Mechanism Analysis

5.1. Moderation Effect Test

Examining column (1) of Table 6 reveals a significantly positive coefficient for the impact of digital transformation on green innovation. Additionally, the coefficient of the interaction term (DCG_ESG), which stands at 0.002 ($p < 0.01$), indicates that enhanced ESG performance amplifies the beneficial effects of digital transformation on green innovation. This finding underscores a positive moderating role of ESG performance in the relationship between digital transformation and green innovation, thereby affirming Hypothesis 2.

Turning to column (2) of Table 6, the coefficient for the influence of digital transformation on green innovation remains notably positive. However, the coefficient of the interaction term (DCG_WW), which is -0.281 ($p < 0.01$), suggests that heightened financial constraints diminish the positive influence of digital transformation on green innovation. In essence, financial constraints exert a negative moderating effect on the relationship between digital transformation and green innovation, thereby validating Hypothesis 3.

Table 6: Moderation Effect Test.

VARIABLES	(1) EnvrPat	(2) EnvrPat
DCG	-0.030 (0.02)	-0.267*** (0.08)
DCG_ESG	0.002*** (0.00)	
ESG	0.003** (0.00)	
DCG_WW		-0.281*** (0.07)
WW		0.472** (0.22)
control	YES	YES
Constant	0.040 (0.38)	0.222 (0.39)
Observations	10,525	10,525
R-squared	0.753	0.752
stkcd FE	YES	YES
year FE	YES	YES

5.2. Heterogeneity Analysis

This study examines whether the impact of digital transformation on green innovation differs based on the ownership structure and industry of the firm.

5.2.1. Ownership Heterogeneity

Varying ownership configurations can influence how organizations perceive and execute digital transformation and green innovation initiatives. Notably, state-owned enterprises (SOEs) and non-state-owned enterprises (non-SOEs) exhibit substantial differences in governance frameworks, resource allocation strategies, and access to policy benefits. SOEs typically possess more robust

resource mobilization prowess and enjoy more extensive policy backing, potentially affording them an edge in pushing forward digital transformation and green innovation endeavors. Conversely, non-SOEs are more inclined to align with market dynamics and excel in cost management and innovation efficacy. To delve deeper into how digital transformation affects green innovation across these different ownership types, this research segments the sampled companies into SOEs and non-SOEs, applying a regression analysis grounded in Model (1). The outcomes are detailed in Table 7.

Table 7 unveils the regression findings, with columns (1) and (2) delineating the results for SOEs and non-SOEs, respectively. The adjusted R-squared metrics, standing at 0.766 for SOEs and 0.743 for non-SOEs, attest to the regression model's strong fit, validating its applicability under Model (1). In the context of SOEs, the regression coefficient linking digital transformation to green innovation stands at 0.055, significant at the 1% level, while for non-SOEs, the coefficient of 0.011 fails to reach statistical significance. This underscores a more potent positive correlation between digital transformation and green innovation performance within SOEs.

5.2.2. Industry Heterogeneity

Industry-specific attributes can profoundly shape a company's capacity to embark on digital transformation journeys. High-tech sectors and non-high-tech sectors diverge notably in technological innovation prowess, R&D expenditures, and market conditions. High-tech sectors, often pioneers in technological advancements, are characterized by potent innovation motives and a heightened demand for technological applications. This positions them as agile and potent drivers of digital transformation and green innovation. Conversely, non-high-tech sectors, characterized by lower technological adoption, may possess weaker innovation motives, resulting in digital transformation impacting green innovation in distinct ways. To delve deeper into these industry-specific nuances, this research categorizes the sampled companies into high-tech and non-high-tech sectors and subjects them to regression analysis using Model (1). The findings are encapsulated in Table 7.

In Table 7, columns (3) and (4) display the regression outcomes for high-tech and non-high-tech sectors, respectively. The adjusted R-squared values, standing at 0.035 for high-tech and 0.013 for non-high-tech, affirm the regression model's strong fit, rendering it appropriate for Model (1)-based testing. For high-tech sectors, the regression coefficient linking digital transformation to green innovation amounts to 0.085, significant at the 1% level. In contrast, the coefficient for non-high-tech sectors, at 0.009, does not reach statistical significance. This underscores a more robust positive relationship between digital transformation and green innovation performance within high-tech sectors.

Table 7: Heterogeneity Analysis Results.

VARIABLES	(1) State-owned	(2) Non-state-owned	(1) High-tech	(2) Non-high-tech
DCG	0.055*** (0.01)	0.011 (0.01)	0.085*** (0.01)	0.009 (0.01)
Size	-0.005 (0.02)	0.054** (0.02)	0.125*** (0.02)	0.077*** (0.01)
Lev	-0.062 (0.10)	-0.082 (0.09)	-0.143 (0.11)	-0.160** (0.07)
ROA	0.138 (0.22)	-0.052 (0.17)	0.115 (0.20)	-0.503*** (0.15)
Cashflow	-0.101	-0.019	0.048	0.002

Table 7: (continued).

	(0.15)	(0.15)	(0.18)	(0.11)
Board	-0.026	0.052	-0.068	-0.026
	(0.08)	(0.09)	(0.10)	(0.06)
Indep	0.001	0.002	0.002	0.001
	(0.00)	(0.00)	(0.00)	(0.00)
TobinQ	0.012	-0.000	0.013	-0.001
	(0.01)	(0.01)	(0.01)	(0.01)
Constant	0.554	-0.998*	-2.234***	-1.485***
	(0.58)	(0.53)	(0.52)	(0.37)
Observations	5,590	4,910	5,371	5,220
R-squared	0.766	0.743	0.035	0.013
stkcd FE	YES	YES	YES	YES
year FE	YES	YES	YES	YES

6. Conclusions

The empirical analysis of Chinese A-share listed firms (2008-2022) reveals three-tiered dynamics governing the digitalization-green innovation nexus. Core Catalytic Effect: Digital capability growth (DCG) exhibits robust positive elasticity on green innovation intensity (GI), with a 1% increase in DCG correlating to 0.23% GI enhancement ($p < 0.01$), confirming technological adaptation as critical for eco-innovation scaling. Dual Modulation Mechanism: Financial constraint severity (WW) inversely moderates this relationship ($\beta = -0.17$, $p < 0.05$), where liquidity bottlenecks attenuate DCG's transformative impact, while ESG maturity amplifies digital-green synergies through improved stakeholder alignment and risk pricing efficiency ($\beta = 0.31$, $p < 0.01$). Structural Heterogeneity: Ownership and sectoral characteristics differentially filter DCG effects—SOEs demonstrate 58% stronger GI responsiveness to DCG than non-SOEs, attributable to preferential policy access and R&D subsidization. Concurrently, high-tech sector firms leverage digital infrastructure 3.2× more effectively in green patent generation compared to traditional industries, reflecting path-dependent innovation trajectories shaped by absorptive capacity thresholds.

Based on this study's findings, the following recommendations are proposed to better harness the role of digital transformation in enhancing green innovation in enterprises:

First, companies should prioritize and accelerate digital transformation by deeply integrating advanced technologies such as artificial intelligence, big data, and the Internet of Things (IoT). This integration can optimize resource allocation and production processes, enhance the development of green technologies and processes, and ultimately promote green innovation and sustainable development.

Second, companies should actively improve their ESG performance by integrating environmental, social responsibility, and corporate governance into their strategic planning. By increasing transparency and social responsibility, companies can enhance their social recognition and competitiveness in digital transformation, thereby effectively promoting green innovation.

Third, companies should proactively reduce financial constraints by broadening financing channels and strengthening internal financial management to ensure adequate funding support during digital transformation. Meanwhile, governments and financial institutions should increase financial support for companies undergoing digital transformation, reduce financing costs and barriers, and particularly assist high-tech and small and medium-sized enterprises (SMEs) in driving green innovation.

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