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A Study on the Mechanism between Digital Transformation and Green Innovation under Financing Constraints

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Abstract: Merging digital frameworks with real-sector operations fundamentally drives enterprise growth. Yet, excessive digital investments may unintentionally suppress intrinsic innovation capabilities. This operational paradox continues to provoke significant scholarly dispute. We collected data from Chinese A-share listed firms spanning 2007 to 2022. Using this sample, we test how digital changes impact corporate green innovation. We specifically explore their non-linear pattern. We also check if financial limits change this dynamic. The data clearly shows an inverted U-shaped trend connecting digital efforts and green innovation; while initial digital investments reduce information asymmetry and boost innovation, excessive digitalization leads to resource crowding-out and human-machine mismatches, ultimately inhibiting green innovation output. Furthermore, financing constraints serve as a critical moderating mechanism. High financing constraints exacerbate the resource squeeze, weakening the early-stage promotion effect of digital transformation and accelerating the onset of its inhibitory effect. Ultimately, the findings yield practical takeaways, guiding companies to align their digital upgrade speeds with their actual funding capabilities.

1. Introduction

Amidst contemporary global market expansions, the widespread deployment of IT technologies has permeated all aspects of corporate operations and societal functions. Executing an IT overhaul is now an essential condition for driving superior corporate development. As highlighted within the 14th Five-Year Plan framework, the rapid progression of internet technologies provides unprecedented opportunities for global industrial integration. Consequently, national policies have continuously emphasized merging virtual networks with physical operations, alongside the fusion of traditional manufacturing and modern data systems. Driven by both policy incentives and market demands, the nation's tech-driven sector expanded to 53.9 trillion yuan by 2023, representing 42.8% of the total GDP[1]. This macroeconomic indicator demonstrates that data-driven sectors function as a core foundation for long-term, superior growth.

However, alongside this rapid macro-level growth, micro-level enterprise transformations face complex realities. Policymakers and industry leaders have warned that during the structural

embedding of AI, data analytics, and cyber networks within legacy sectors, enterprises must remain grounded and tailor their strategies to their specific conditions. The phenomenon of "digitizing for the sake of digitizing" has sparked growing concerns. Such phenomena imply while technological upgrading within the real economy is the overarching theme, "over-digitalization" has emerged as a practical operational hazard, potentially leading to distorted resource allocation and diminished innovation returns.

Existing mainstream literature regarding how IT integration shapes enterprise innovativeness remains divided across two primary perspectives. One first perspective emphasizes the positive empowerment of digitalization. Deep digital transformation enhances management efficiency, drastically reduces production and transaction costs, and thereby provides robust internal control guarantees for technological innovation[2]. Furthermore, digitalization mitigates information asymmetry, strengthens positive market expectations, directly promotes corporate R&D investment and innovation output, and enhances overall corporate value and financial stability. Conversely, the second perspective focuses on the pitfalls of "over-digitalization." Researchers argue that while moderate digital transformation effectively improves corporate performance, excessive transformation causes human-machine mismatches, resulting in corporate profit losses[3]. Particularly in heavy-polluting manufacturing sectors, an over-reliance on digital upgrades can crowd out existing resources, suppress overall productivity enhancements, subsequently poised to exertadverse structural effects on enduring resource allocation.

Given the conflicting viewpoints, this paper aims to clarify the precise impact boundary driven by IT adoption on environmental advancements. We hypothesize this dynamic proves not purely linear instead forming an inverted U-shape characterized by a "digitalization paradox." Moreover, technological innovation and digital system overhauls are both highly capital-intensive activities. Therefore, this paper employs "financing constraints" as a key moderation mechanism to explore how capital availability dictates an enterprise's ability to balance digital expenditures and green R&D. By doing so, this study expands existing literature regarding the micro-level consequences of digitalized operations and provides actionable guidance for corporate strategic planning.

2. Theoretical Framework and Hypotheses

2.1 The Nexus between Digital Upgrades and Enterprise Green Innovation

Corporate digital transitions rely on fundamental technologies, including AI and blockchain architectures. These strategic upgrades primarily seek to optimize internal governance and boost operational productivity. Regarding eco-friendly outputs, the affordance theory within digital technology posits that the realization of transformation goals is influenced not only by the technology itself but also by how the enterprise utilizes it[4].

During the early and moderate phases of tech integration, this "resource effect," "governance effect," and "multiplier effect" dominate. By introducing cutting-edge digital technologies, enterprises can optimize internal information flow channels and dismantle data silos. This reduction in information asymmetry enables management to swiftly grasp market demands and technological frontiers, allowing them to precisely increase R&D funding and rationally plan project trajectories. Simultaneously, digital tools optimize production processes, improve efficiency, and lower operational costs. This cost-saving mechanism frees up crucial financial and human resources, transferring them directly into green technological innovation activities, thereby elevating the enterprise's overall innovation capacity.

However, according to the spillover effect theory of digital information, the continuous upgrading of IT systems is driven by profit motives, but like other factor inputs, it exhibits a clear marginal diminishing effect. When digital technology's innovation spillover reaches its peak, the

marginal benefit drops to zero. If an enterprise blindly pursues deeper digitalization beyond its absorptive capacity, the "digitalization paradox" occurs[5]. Excessive digital investments lead to severe human-machine mismatches, soaring employee training costs, and exorbitant equipment maintenance fees. Furthermore, the sheer complexity of advanced digital systems may exceed the enterprise's managerial capability, making it difficult to translate these technologies into actual innovation outcomes. Especially under the condition that an enterprise's total resource pool is relatively fixed, massive capital tilted toward IT infrastructure will inevitably cause a severe "resource displacement" for environmental research resources, shifting innovation performance from good to bad. Consequently, this logic leads to our initial assumption.

H1: Digital transition exercises a non-linear, inverted U-shaped impact on enterprise green innovation.

2.2 The Moderation Mechanism of Capital Limitations

Capital shortages represent the structural boundaries enterprises face during the capital acquisition process, typically manifesting as capital shortages or prohibitively high financing costs. Due to smaller scales and severe information asymmetry, many enterprises—particularly non-state-owned SMEs—are highly susceptible to financing constraints[6]. These constraints directly limit not only an enterprise's capital acquisition capabilities but also its capacity for innovation and strategic expansion.

When an enterprise faces high financing constraints, its capital acquisition channels are narrow, and its total available funds are strictly limited. Under such precarious financial conditions, pursuing digital transformation forces the enterprise into a harsh trade-off. Because highly constrained enterprises have stretched capital chains, they cannot simultaneously shoulder the massive, ongoing costs of digital transformation and the highly uncertain, long-cycle investments required to achieve green technical breakthroughs. Consequently, the displacement of funds becomes prominent much earlier. The enterprise is forced to compress its green innovation inputs and lower its tolerance for experimental failures, causing the added value of IT transformation to reach its peak prematurely.

Conversely, enterprises with low financing constraints possess robust capital reserves. They can leverage diverse channels (equity, debt, state subsidies) to guarantee the smooth, parallel advancement of both digital infrastructure building and green R&D. The abundant financial buffer mitigates the resource squeeze, allowing the enterprise to push its digital transformation to a deeper level before experiencing any negative crowding-out effects on innovation. In summary, higher capital limitations dilute the initial promotional benefits from digitalization and accelerate an early onset of its inhibitory effect. Therefore, we propose the second hypothesis:

H2: The inverted U-shaped curve linking digital transformation to enterprise green innovation is moderated by capital limitations.

3. Research Design

3.1 Sample Selection and Data Sources

Our primary data originates from the CSMAR system. The initial timeframe covers 2007 to 2022 for entities listed on the Chinese A-share market. We clean this raw sample using three strict criteria to guarantee estimation accuracy. First, we omit property developers and financial institutions. Second, we drop troubled firms holding ST, *ST, or PT labels to rule out operational distress biases. Third, we delete any records lacking essential metrics. To mitigate the impact of abnormal fluctuations, continuous variables undergo a 1% level winsorization on both tails. Consequently, we

obtain a finalized panel containing precisely 38,327 firm-year observations.

3.2 Variable Definitions

Dependent Variable: Corporate Green Innovation (Inn). Following established literature, this study uses the number of green invention patent applications to measure green innovation[7]. The rationale for choosing application volume over authorization volume is that applications more accurately and immediately reflect the enterprise's green innovation intent and capability in the current year. Patent authorizations typically suffer from a 1 to 2-year bureaucratic lag and are influenced by external institutional efficiencies.

Independent Variable: Digital Transformation (Dig). This paper utilizes text mining methodologies on corporate annual reports. By constructing a dictionary of "underlying technology applications" (encompassing artificial intelligence, big data, cloud computing, and blockchain) and "technology practical applications," we used Python to crawl relevant keywords and calculate their frequencies[8]. These raw frequency counts exhibit significant positive skewness. We mitigate this by adding one to each count prior to applying a natural logarithmic transformation. This adjusted metric subsequently serves as our primary digitalization proxy.

Moderating Factor: Capital Limitations (SA). This study employs the SA metric for this measurement tool. Because the firm-size parameter within its underlying equation carries a negative sign negative, the index usually presents as a negative value. To facilitate the interpretation of the moderation effect, this paper takes the absolute value of this computed metric. A greater absolute figure reflects more severe funding constraint. The SA index is preferred as it avoids endogeneity issues and relies solely on firm size and age, eliminating the need for complex internal financial indicators that could cause multicollinearity.

Covariates: To isolate the effect of digitalization, we incorporate an array of enterprise-level controls. Our models account for total assets (Size) and debt-to-asset ratios (Lev) to capture basic firm characteristics. We evaluate profitability through Return on Assets (ROA) and expansion momentum via Revenue Growth Rate (Growth). Governance metrics consist of board independence (Indep) and the separation of chairman and chief executive duties (Dual). Finally, market valuation (TobinQ) and listing history (FirmAge), as show in table 1.

Table 1. Summary of variable measurements.

Variable Type	Variable Symbol	Variable Name
Dependent Variable	Inn	Corporate Green Innovation
Core Explanatory Variable	Dig	Digital Transformation
Moderating Variable	SA	Financing Constraints
Control Variables	Size	Firm Size
Control Variables	Lev	Leverage Ratio
	ROA	Return on Assets
	Growth	Revenue Growth Rate
	Indep	Independent Director Ratio
	Dual	CEO Duality
	TobinQ	Tobin's Q
	FirmAge	Firm Listing Age
	Pay	Executive Compensation

3.3 Model Construction

To empirically test Hypothesis 1, we construct the following baseline fixed-effects regression model:

$$Inn_{it} = \alpha_0 + \alpha_1 Dig_{i,t} + \alpha_2 Dig_{i,t}^2 + \alpha_3 \sum \text{Controls}_{i,t} + \text{Firm\_FE} + \text{Year\_FE} + \varepsilon \quad (1)$$

In Equation (1), Inn represents corporate green innovation, while Dig and Dig^2 represent the linear and squared terms of digital transformation, respectively. We incorporate Firm_FE and Year_FE to absorb unobserved entity-specific variations and temporal macroeconomic fluctuations. All control variables described above are included. ε is the random error term.

To test Hypothesis 2, we introduce the cross-product terms linking funding restrictions with the linear/squared terms of digital transformation into the baseline model, constructing Equation (2):

$$Inn_{it} = \alpha_0 + \alpha_1 Dig_{i,t} + \alpha_2 Dig_{i,t}^2 + \alpha_3 Dig_{i,t} \times SA + \alpha_4 Dig_{i,t}^2 \times SA + \alpha_5 \sum \text{Controls}_{\text{i,t}} + \text{Firm\_FE} + \text{Year\_FE} + \varepsilon \quad (2)$$

4. Empirical Analysis

4.1 Descriptive Statistics

A statistical summary of all primary metrics appears in Table2, covering the 38,327 observations. Corporate green invention patent applications (Inn) average 10.29, indicating a baseline level of green innovation capability across the sample. However, the standard deviation is notably high at 80.70, with a maximum of 3,414, highlighting severe polarization and significant disparities in green innovation performance among different enterprises. Digital transformation (Dig) yields an average of 11.10. It exhibits a standard deviation of 29.55, reflecting that while digital transformation is underway, the depth of implementation varies drastically; some firms are pioneers, while others remain in the nascent stages. The financing constraint (SA) records an average score of -3.814. Its standard deviation stands at 0.282. This indicates that sample enterprises sample enterprises generally face considerable financial pressure. The remaining covariates exhibit distributional patterns consistent with the standard characteristics of Chinese listed companies.

Table 2. Summary statistics of key variables.

VARIABLES	N	Mean	SD	Min	Max
Inn	38,327	10.29	80.70	0	3,414
Dig	38,327	11.10	29.55	0	544
SA	38,327	-3.814	0.282	-5.931	-1.805
Size	38,327	22.14	1.318	15.58	28.64
Lev	38,327	0.436	0.209	0.00708	1.545
ROA	38,327	0.0380	0.0788	-1.859	1.285
Growth	38,327	4.457	692.0	-0.999	134,607
Indep	38,327	37.48	5.620	0	100
Dual	38,327	0.269	0.444	0	1
TobinQ	38,327	2.123	2.508	0.609	259.1
FirmAge	38,327	2.884	0.355	0.693	4.174
Pay	38,327	15.25	0.813	9.385	18.84

4.2 Empirical Estimations

Table 3 outlines the primary regression outcomes. This section assesses how enterprise digitalization affects green innovation. The first specification presents a basic model. It retains just the main variables, controlling for entity and time fixed effects. Specification (2) introduces all enterprise-specific covariates. Specification (3) subsequently integrates our financing constraint moderator and its interaction terms to verify the moderating mechanism. The Hausman test was conducted, confirming the applicability of the fixed-effects model across all specifications.

Table 3. Primary estimation outcomes.

VARIABLES	(1)innlv	(2)innlv	(3)innlv
Dig	0.154*** (5.38)	0.129*** (4.44)	3.642*** (10.12)
Dig2	0.000*** (-4.78)	0.000*** (-4.38)	-0.011*** (-7.14)
SA			131.297*** (33.03)
SA*Dig			-0.875*** (-9.65)
SA*Dig2			0.003*** (6.89)
Size		5.155*** (8.18)	4.429*** (7.16)
Lev		-10.525*** (-4.23)	-7.320*** (-3.00)
ROA		-1.885 (-0.45)	1.507 (0.37)
Growth		0.000 (0.14)	0.000 (0.16)
Indep		0.112* (1.66)	0.082 (1.24)
Dual		2.603*** (2.98)	1.854** (2.16)
TobinQ		0.180 (1.42)	-0.992*** (-7.69)
FirmAge		9.862*** (2.76)	11.567*** (3.22)
Pay		-2.180*** (-3.18)	-1.209* (-1.79)
Cons	9.118*** (26.90)	-100.636*** (-5.78)	397.587*** (17.88)
Observations	37,873	37,873	37,873
R-squared	0.669	0.670	0.683
Firm FE	YES	YES	YES
Year FE	YES	YES	YES

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Main predictor outcomes in Column (2) demonstrate that after controlling for time trends, individual heterogeneity, and firm characteristics, the first-order estimate for digital transformation (Dig) displays a positive sign at the 1% threshold (0.129, t=4.44). Crucially, quadratic parameter squared term (Dig^2) proves notably negative at the 1% level (-0.000, t=-4.38). This indicates that the promotional effect of digital transformation on green innovation experiences marginal diminishing returns. By calculating the inflection point, we find that when the Dig value reaches approximately 158 (compared to the sample mean of 11.1), the promotional effect transitions into an inhibitory effect. These statistics imply that the tech-driven boost to ecological R&D, a minority of top-tier enterprises engaging in aggressive, unchecked digitalization face severe over-transformation risks, leading to resource crowding-out. Thus, Hypothesis 1 is robustly verified.

In Column (3), after introducing financing constraints (SA) and its interaction terms, the model's R-squared improves to 0.683, indicating enhanced explanatory power. The main effect of financing constraints (SA) is positive, aligning with resource dependence theory, which suggests that highly constrained firms may paradoxically engage in green innovation specifically to secure targeted government subsidies and green credit. More importantly for our study, the SA x Dig product yields a robust negative value (-0.875, t=-9.65), and the SA x Dig^2 component emerges as notably positive (0.003, t=6.89).

This configuration of coefficients proves that capital limitations flatten this non-linear parabolic trajectory. They concurrently force the turning point to appear earlier. This economic implication is twofold: First, during the initial phase of digital transformation, capital shortages force highly constrained enterprises to compress R&D budgets to fund IT infrastructure, weakening the positive "resource effect" of digitalization. Second, as digitalization deepens, the lack of a financial buffer eliminates the enterprise's tolerance for trial-and-error. The fundamental contradiction between the massive capital required for IT maintenance and the long-term investment needed for green innovation accelerates. Consequently, management is forced to drastically cut green R&D to survive, meaning the inhibitory effect of "over-digitalization" arrives much faster for firms plagued by financing constraints. Hypothesis 2 is thereby confirmed.

5. Conclusion

This research utilizes an extensive panel of Chinese publicly traded firms spanning 2007 to 2022. We evaluate the intricate, non-linear dynamics linking IT integration to eco-friendly advancements. The empirical analysis produces two primary takeaways. Initially, the evidence confirms a distinct parabolic curve connecting technological upgrades with environmental R&D. Moderate digitalization bridges information gaps and optimizes resource allocation, yet excessive, blind digitalization triggers a "digitalization paradox," culminating in resource crowding-out and human-machine mismatches that stifle green R&D. Second, financing constraints act as a powerful moderating force. Severe capital constraints not only dilute the early-stage innovation dividends of digitalization but also critically accelerate the onset of its negative, crowding-out phase.

These findings offer vital practical implications. For corporate management, digital transformation should not be viewed as an unconditional panacea. Enterprises must scientifically plan their digital roadmaps based on their actual capital endowments and absorptive capacities, avoiding the trap of "digitizing for the sake of digitizing." For policymakers, it is imperative to construct a more inclusive and targeted green finance system. By actively lowering the financing constraints for SMEs engaged in dual transitions (digital and green), the government can extend the positive window of digital empowerment, ensuring that capital shortages do not force enterprises to sacrifice sustainable green innovation for basic IT survival.

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