Digital Transformation, R&D Investment and Green Innovation

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Abstract. This empirical investigation evaluates how corporate digital initiatives affect sustainable technological advancements, utilizing a comprehensive dataset comprising authenticated financial records from Chinese A-share market entities spanning the decade from 2013 through 2023. Empirical findings demonstrate a quantitatively measurable constructive linkage connecting organizational technological transformation with environmental innovation strategies. Furthermore, this causal relationship remained robust when implementing alternative proxy variables during methodological validation procedures covering multiple robustness check scenarios. Building upon this analytical framework, the study incorporates R&D expenditure as a mediator to systematically investigate the transmission pathways through which organizational digitalization strategies influence sustainable innovation practices. Empirical findings demonstrate that technological modernization enhances eco-innovation outcomes via their stimulating effects on research capital allocation; statistical validation procedures confirm the hypothesized mediation mechanism exhibits statistically robust explanatory power (p<0.01).This research advances existing literature on determinants of R&D capital allocation while establishing a theoretical framework for corporate strategic prioritization of digital ecosystems and sustainable innovation. The developed model demonstrates how optimizing technological adoption pathways and eco-innovation capabilities synergistically drives enterprise value creation, offering empirical guidance for achieving sustainable growth through innovation-driven transformation.

Keywords: digital transformation, green innovation, R&D investment

1. Introduction

Under the macro picture of the deep adjustment of the global economic structure and the synergistic promotion of the construction of ecological civilization, the new economic form driven by digital technology and the sustainable development strategy oriented to low-carbon transformation are becoming the key dimensions of reshaping the global competition pattern. In the context of accelerating global climate governance and deepening China's "dual-carbon" strategy, eco-innovation now serves as a pivotal mechanism enabling corporations to achieve environmentally-conscious growth while cultivating climate-resilient market advantages aligned with carbon neutrality objectives [1].

Serving as a strategic catalyst for achieving carbon neutrality objectives, sustainable technological innovation is fundamentally reshaping industrial production models and energy consumption patterns within the framework of sustainable development paradigms. This transformation is accelerating the transition of contemporary economic systems toward sustainable resource allocation mechanisms, as evidenced by recent academic investigations [2].Eco-innovation fundamentally differs from conventional innovation models in corporate operations, demonstrating exponential increases in technological sophistication and extended implementation cycles. These distinctive techno-economic attributes necessitate substantial innovation capital allocation, posing significant challenges to organizational R&D budgeting systems. Consequently, the adequacy of innovation funding emerges as a critical determinant for successful adoption of sustainable technological solutions in industrial practices [3].

With the vigorous development and application of digital technology, the enterprise digital revolution, as the core carrier for improving organizational resilience and technological competitiveness, has evolved from a pure technology application to a complex system engineering covering strategic restructuring, process reengineering and capability leapfrogging. This change not only realizes the dynamic optimization of the operation system and the exponential improvement of the decision-making efficiency, which greatly improves the total factor productivity [4], more critically, this process establishes foundational technological infrastructure essential for driving environmentally-conscious innovation, while simultaneously accelerating organizational digital modernization across business ecosystems. Existing research shows that the introduction of digital technology in enterprises can greatly improve the level of resource integration and allocation, reduce costs, improve efficiency, maximize the flexible use of enterprise resources to achieve sustainable economic development [5], enabling enterprises to more effectively invest funds in research and development, and providing a strong support and solid foundation for green innovation [6]. Consequently, systematic investigation into how organizational digitalization impacts sustainable innovation practices has emerged as a critical priority in contemporary scholarly discourse. Drawing on data from Chinese publicly traded corporations spanning the decade between 2013 and 2023, this investigation systematically evaluates the effects of organizational digitalization processes. By employing rigorous econometric analysis, the study elucidates the relationships between technological modernization and innovation capital allocation, particularly in driving environmentally sustainable technological advancements.

The core research questions of this study are (1) How does the adoption of intelligent technologies contribute to the advancement of eco-innovation processes in corporate settings? (2) Does innovation capital allocation function as a mediating mechanism between technological modernization initiatives and environmental innovation outcomes? (3) Does the mechanism work differently under different property rights properties? By empirically analyzing the panel data of Chinese A-share listed companies from 2013-2023, this paper adopts the double fixed effects model with the mediation test to systematically examine the transmission path of strategic adoption of intelligent technologies affecting green innovation through R&D investment.

This research advances scholarly understanding through dual academic contributions: (1) expanding the theoretical discourse on technological digitization's impact on sustainable innovation, and (2) establishing methodological frameworks that inform future explorations in this emerging field. Secondly, the study further investigates the intermediary mechanisms of innovation expenditure, expanding theoretical insights into technology-enabled sustainable innovation. This analytical progression plays a vital role in facilitating coordinated progress between industrial advancement and ecological conservation.

2. Research hypothesis

2.1. Digital modernization and sustainable innovation synergy

Given the pervasive adoption of digital tools across various sectors, the enterprise production efficiency [4] and information collection and integration capabilities have been greatly improved [7], thus promoting the acceleration of the pace of digital transformation, which has a great impact on the enterprise research and development of green innovation technology [8].

Digitization maturity progression refers to the change driven by digital technology, which is integrated into enterprise production and R&D to help enterprises improve operational efficiency and R&D speed, and quickly collect and integrate information to realize transformation and upgrading, greatly promoting the efficiency of realizing the results of enterprises' green innovation outputs [9] and the ability of independent innovation [10].For one thing,the integration of intelligent systems fundamentally reshapes corporate innovation processes. By adopting cloud-based platforms, AI-driven analytics, and interconnected supply networks, businesses achieve enhanced capability in sourcing critical R&D materials [11]. This technological convergence significantly lowers experimental expenditures [12], mitigates data accessibility challenges, and improves decision-making precision. Consequently, organizations can streamline information acquisition timelines while allocating greater resources to product development cycles. The realization of the process, improve the efficiency of scientific research output, accelerate the realization of the sustainable development of the economy under the guidance of green innovation. For another thing, the technological modernization of business operations enables multifaceted enhancement in data management capacities [13]. Through intelligent system integration, organizations can expand their data gathering breadth while deepening analytical processing capabilities. This digital progression facilitates real-time interpretation of R&D metrics, allows strategic evaluation of research path viability, and creates diversified implementation channels for sustainable innovation initiatives. Collectively, these structural enhancements drive concurrent scale enlargement and quality optimization within sustainable innovation outcomes [14].

Based on the above analysis, this paper presents the hypothesis:

H1: Digital transformation has a catalytic effect on green innovation.

2.2. Digital transformation, R&D investment and green innovation

The "14th Five-Year Plan" clearly puts forward "to digital transformation to drive the overall change of production mode", marking the enterprise green innovation is facing the double change of technology path and organizational form. In this regard, it has been shown in the literature that the realization of digital transformation as a whole drives the change of production methods, and the R&D process requires substantial financial support to ensure the smooth implementation of R&D activities and the stability of the process [15]. In addition, digital transformation has the characteristics of optimizing resource allocation [16], the deep integration of enterprise core resources and digital technology, the formation of the optimal decision-making path based on real-time data analysis [17], and significantly reduce redundant expenditures, such as energy waste and human resources duplication of inputs in traditional processes. This adaptive resource allocation system enhances financial flexibility, enabling enterprises to optimize the utilization of scarce organizational assets through cost containment strategies. By curbing non-essential operational expenses, such mechanisms create fiscal space for dedicated innovation funding, thereby boosting the effectiveness of eco-friendly technological advancements [18].

To foster innovative practices, a portion of research and development budgets may be designated as performance-based rewards for project teams, thereby encouraging creative engagement and advancing sustainable business initiatives. Such financial incentives serve not only to bolster researchers' dedication but also to facilitate organizational transitions toward environmentally conscious innovation strategies. By strategically directing monetary resources toward talent motivation mechanisms, enterprises can effectively cultivate a culture of continuous improvement in eco-friendly technological development.

Based on the above analysis, this paper presents the hypothesis:

H2:Digital transformation through R&D investment and thus green innovation.

3. Research design

3.1. Sample selection and data sources

A-share listed companies from 2013 to 2023 are taken as the research object to empirically examine the impact of digital transformation on the green innovation capability of enterprises. The samples of listed companies are mainly from CSMAR database and are screened as follows: (1) financial and insurance companies are excluded; (2) ST and *ST companies are excluded; (3) companies with missing data are excluded; and (4) in order to eliminate the influence of outliers, this paper shrinks the continuous variables at the level of 1%~99%. Finally, 27,467 valid observations are obtained.

3.2. Measurement of variables

3.2.1. Explained variable: corporate green innovation (Gti1)

Building upon prior research frameworks [19] , this study utilizes the cumulative count of eco-friendly patent filings (Gti1) during the reporting cycle as a quantitative indicator for evaluating enterprises' sustainable innovation capacities. Due to the right-skewed distribution problem of green invention patent applications, in order to more accurately measure green technological innovation, this paper adopts the treatment of adding 1 to take the natural logarithm.

3.2.2. Explanatory variables: digital transformation (Digword)

Drawing on the research methods in the literature [20], we collect and organize the relevant keywords about digital transformation through Python crawler technology, search, match and count the word frequency according to the keywords, and then form the final total word frequency, so as to construct the index that can measure enterprise-system digital convergence.To address asymmetric distribution patterns in the dataset, this research implements logarithmic transformation, thereby developing a composite metric for holistically assessing corporate digital transition progress.

3.2.3. Mediating variable: research and development (R&D) investment

Using firms' R&D investment as a percentage of operating revenue as a proxy variable for firms' R&D investment intensity.

3.2.4. Control variables

Drawing on existing literature to select control variables [20,21]. This paper mainly selects control variables from three aspects of company characteristics, financial characteristics and governance characteristics, as well as variables such as industry (ind) and year (year), so as to exclude the potential impact of other factors on corporate green innovation. In this paper, the following control variables are selected: firm size (Size), gearing ratio (Lev), firm age (Age), board size (Board), shareholding concentration (Top10), nature of equity (SOE), net profit growth rate (NetProfitGrowth)

All variables are defined as shown in Table 1:

Table 1. Definition of variables

Variable type	variable name	variable symbol	Variable design
explanatory variable	Corporate Green Innovation	Gti1	Total green patent applications for the period
		Gti2	Total number of green patents granted during the period
explanatory variable	Digital Transformation	Digword	Natural logarithm of keyword frequency
intermediary variable	R&D investment	R&D	R&D investment as a percentage of operating revenue
control variable	Enterprise size	Size	Natural logarithm of total assets
	gearing	Lev	Total liabilities at the end of the period / Total assets at the end of the period
	Age of business	Age	Natural logarithm of the number of years since the date of enumeration minus the number of years since the date of establishment of the enterprise
	Board size	Board	Natural logarithm of the number of board members
	shareholding concentration	Top10	Shareholding ratio of top ten shareholders
	Nature of shareholding	SOE	1 for state-owned enterprises, 0 for non-state-owned enterprises
	Net profit growth rate	NetProfit Growth	Net Profit Current Current Single Quarterly Amount - Net Profit Previous Single Quarterly Amount / Net Profit Previous Single Quarterly Amount

3.2.5. Modeling

This study employs a dual fixed-effects model to evaluate digitalization's impact on eco-innovation. Following prior methods [22], the design integrates temporal and entity controls for robust analysis.

$$Gti1_{i,t} = \alpha_0 + \beta Digword_{i,t} + \sum \gamma_i Controls_{i,t} + \sum Year + \sum Ind + \varepsilon_{i,t} \qquad (1)$$

Where the explanatory variable Gti1 is firms' green innovation. Controls$_{i,t}$ is all control variables for firm i in year t. Ind and Year indicate that the model controls for firm industry effects and year effects. $\varepsilon_{i,t}$ is the model random error term.

In order to test the role of mediating mechanism of R&D investment, models (2) and (3) are constructed to study the mediating role of R&D investment by adopting the approach of existing literature [23].

$$R\&D_{i,t} = \alpha_1 + \beta_1 Digword_{i,t} + \sum \gamma_i Controls_{i,t} + \sum Year + \sum Ind + \varepsilon_{i,t} \qquad (2)$$

$$Gti1_{i,t} = \alpha_1 + \beta_1 Digword_{i,t} + \beta_2 R\&D + \sum \gamma_i Controls_{i,t} + \sum Year + \sum Ind + \varepsilon_{i,t} \qquad (3)$$

Within the analytical framework, Model (2) employs R&D expenditure as an independent variable to investigate how digital transformation influences innovation investment. Building upon this foundation, Model (3) incorporates the mediating component of R&D spending to assess its intermediary role in linking technological digitization with sustainable innovation practices.

4. Empirical results and analysis

4.1. Descriptive statistics

Table 1 presents the descriptive statistics of the main variables. Statistical analysis reveals that the Digital Transformation Index scores range from 0 to 5.220, with an average of 1.670. This indicates that corporate digitization initiatives remain at a nascent phase, requiring further strategic advancement. Moreover, substantial inter-firm disparities in implementation progress highlight uneven adoption patterns across enterprises. It is particularly noteworthy that there is an extreme value of 0 in the data, which reveals that among listed companies, there are still some enterprises that follow the traditional business management mode and have not yet started the pace of digital transformation. Benchmarking analysis shows the Green Technology Index (Gti1) demonstrates an average level of 0.410, spanning from zero to 6.620. These metrics suggest notable disparities in sustainable innovation capacities across organizational entities, revealing uneven developmental patterns in environmental technology adoption. Overall, green innovation capability is still in the initial development stage, and the awareness of some listed companies in promoting the deep integration of environmental and economic benefits, and thus promoting the high-quality development of enterprises, still needs to be further improved. Meanwhile, green innovation practices are still in the initial stage and need to be further strengthened. Statistical analysis of innovation expenditure reveals an average R&D intensity of 4.980 across surveyed firms, with values spanning from 0.0300 to 26.48. The median investment level registers at 3.890, demonstrating substantial disparities in research funding allocation relative to operational income. This distribution pattern underscores the heterogeneity in technological investment strategies among enterprises.From the overall trend, listed companies' investment in green innovation R&D field is in a booming stage. The mean and median values of R&D investment indicate that most enterprises maintain a relatively stable level of investment, but the appearance of the maximum value reveals the active exploration and great investment in innovation of some enterprises.

Table 2. Descriptive statistics of main variables

Variable	N	Mean	SD	Min	p50	Max.
Size	27466	22.21	1.280	20	22.01	26.29
Lev	27456	0.380	0.190	0.0500	0.370	0.840
Age	27144	2.890	0.340	1.100	2.940	4.170
Board	27449	2.100	0.200	1.100	2.200	2.890
Top10	27456	60.34	14.66	25.67	61.41	90.70
SOE	27456	0.270	0.450	0	0	1
NetProfitGrowth	27441	-0.550	7.110	-50.51	-0.120	22.50
R&D	27466	4.980	4.660	0.0300	3.890	26.48
Gti1	27446	0.410	0.830	0	0	6.620
Gti2	27446	0.330	0.720	0	0	6.350
Digword	27465	1.670	1.420	0	1.390	5.220
indcode	27466	35.75	15.52	1	33	81

4.2. Benchmarking the return of digital transformation to green innovation

Column (1) of Table 2, shows the regression results of model (1). As shown in column (1) of Table 2, the regression coefficient of Digital Transformation (Digword) is 0.0557 after adding control variables, and statistical significance at the 1% threshold ($p<0.01$) reveals that enterprises demonstrating advanced technological digitization exhibit enhanced competencies in environmental innovation. This finding confirms a robust positive association between digital adoption and sustainable innovation practices, thereby providing empirical confirmation of H1.

Table 3. Mediating effect of digital transformation on green innovation benchmark regression and R&D investment

	(1)	(2)	(3)
	Gti1	R&D	Gti1
Digword	0.0557 *** (0.00441)	0.255 *** (0.0203)	0.0516 *** (0.00441)
Size	0.149 *** (0.00508)	-0.0142 (0.0233)	0.149 *** (0.00507)
Lev	0.153 *** (0.0316)	-5.230 *** (0.145)	0.238 *** (0.0322)
Age	-0.127 *** (0.0157)	-1.003 *** (0.0721)	-0.110 *** (0.0157)
Board	0.0994 *** (0.0254)	0.107 (0.117)	0.0977 *** (0.0253)
Top10	0.000387 (0.000339)	-0.00978 *** (0.00156)	0.000546 (0.000338)
SOE	0.0734 *** (0.0125)	-0.272 *** (0.0575)	0.0778 *** (0.0125)
NetProfitGrowth	0.00168** (0.000661)	-0.00831 *** (0.00303)	0.00181 *** (0.000659)
Year	Yes	Yes	Yes
indcode	Yes	Yes	Yes
RD			0.0162 *** (0.00132)
_cons	-3.304*** (0.147)	6.848 *** (0.677)	-3.415 *** (0.147)
N	27121	27124	27121
R^2	0.178	0.434	0.183
adj. R^2	0.175	0.432	0.180

Standard errors in parentheses

* p < 0.1, ** p < 0.05, *** p < 0.01

4.3. R&D input intermediation

The above results indicate that the degree of digital transformation of enterprises would substantially enhance the operational competencies required for sustainable innovation, considering that it may be that digital transformation optimizes the resource allocation capacity and reduces duplicated and unnecessary expenditures, so that enterprises can invest more funds in R&D, and through the increase in R&D investment, thus promoting the green innovation of enterprises. This research empirically investigates the mediating effects of R&D investment allocation on the correlation between digital transformation of technologies and progress in eco-innovation initiatives through structured analysis. Existing scholarship [24] demonstrates that enhanced corporate research expenditure stimulates eco-innovation capabilities, with this amplifying impact exhibiting cumulative enhancement over time. In this case, empirical observations confirm a robust correlation

between innovation expenditure levels and corporate eco-innovation performance. Enhanced research funding allocation reinforces organizational commitment to technological advancement while optimizing the operational efficacy of sustainable innovation processes. Concurrently, enhancing R&D funding allocations and implementing incentive schemes strengthens scientific staff's creative engagement, thereby optimizing operational effectiveness in corporate sustainability innovation endeavors. This study examines how innovation expenditure mediates the connection between technological digitization and sustainable innovation practices. Empirical evidence suggests that research funding allocation serves as a fundamental driver shaping corporate environmental innovation capacities.

Table 2 reports the regression results of the mediating role of R&D investment between digital transformation and firms' green innovation. As evidenced by Column (2) analytical outcomes, a statistically significant positive association (p<0.01) exists between technological digitization indicators (Digword) and corporate innovation expenditure. This statistical relationship demonstrates the enhancement effect of technological advancement on innovation funding allocation patterns.Column (3) puts digital transformation (Digword)and R&D investment (R&D)into the model at the same time, and the results show that the coefficient of digital transformation (Digword) on enterprise green innovation (Gti1) is still significantly positive at 1% level, which indicates that digital transformation can promote enterprise green innovation by increasing R&D investment. The empirical results demonstrate that innovation expenditure serves as a critical intermediary in linking technological digitization processes with corporate environmental innovation, thereby confirming H2.

4.4. Robustness tests

4.4.1. Variable substitution

In order to verify the robustness of the results, this paper uses the total green patent acquisition in the slot period (Gti2) to replace the explanatory variables. After the test, the results are shown in Table 3. The benchmark analysis in column (1) reveals a statistically significant positive association (p<0.01) for the Digword metric, thereby validating the initial econometric findings through consistent empirical evidence.

Table 4. Results of robustness test and heterogeneity test

	(1)	(2)	(3)
	Gti2	Gti1	Gti1
Digword	0.0335 *** (0.00380)	0.0737 *** (0.0104)	0.0495 *** (0.00473)
Size	0.125 *** (0.00438)	0.199 *** (0.0103)	0.139 *** (0.00600)
Lev	0.144 *** (0.0272)	-0.109 (0.0695)	0.235 *** (0.0348)
Age	-0.104 *** (0.0135)	-0.129 *** (0.0377)	-0.147 *** (0.0168)
Board	0.112 *** (0.0219)	0.275 *** (0.0549)	0.0211 (0.0280)
Top10	0.000315 (0.000292)	-0.00262 *** (0.000779)	0.000940** (0.000378)
SOE	0.0312*** (0.0108)	0 (.)	0 (.)
NetProfitGrowth	0.00104* (0.000569)	-0.000391 (0.00141)	0.00266 *** (0.000728)
Year	Yes	Yes	Yes
indcode	Yes	Yes	Yes
_cons	-2.804*** (0.127)	-4.625 *** (0.277)	-2.699*** (0.193)
N	27121	7498	19623
R^2	0.175	0.231	0.176
adj. R^2	0.172	0.222	0.172

4.5. Heterogeneity test

From the previous study,empirical evidence confirms the catalytic function of digital adoption in driving eco-innovation. Considering innovation characteristics, ownership-based stratified analysis identifies operational variances, with extended examination revealing contextualized mechanisms through which technological upgrades shape sustainability practices. According to China's regulations, enterprises can be divided into state-owned enterprises and non-state-owned enterprises according to the nature of equity.

Columns (2) and (3) of Table 3 clearly show the results of the heterogeneity test based on different nature of equity. The study shows that listed companies belonging to state-owned enterprises (SOEs) exhibit a more significant positive correlation between digital transformation and green innovation compared to non-SOEs. This disparity arises from private firms' constrained resource allocation capacity and delayed information acquisition compared to SOEs, leading to diminished competitive edges in R&D initiatives relative to their state-owned counterparts.Therefore, the positive contribution of digital transformation to corporate green innovation is more significant in state-owned enterprises.

5. Conclusions and insights

This paper selects valid data of all A-shares in China from 2013 to 2023, empirically tests the impact of digital transformation on green innovation, and examines the mediating effect of R&D investment between digital transformation and green innovation.The empirical analysis confirms two principal insights: (1) technological digitization exerts a significant positive influence on environmental innovation outcomes; (2) innovation expenditure levels serve as a key mediating pathway through which digital adoption facilitates sustainable innovation practices.

These empirical findings elucidate the pathways through which technological digitization effectively strengthens sustainable innovation capabilities and operational efficacy. The "14th Five-Year" national strategic blueprint strategically emphasizes fostering innovation-led development paradigms to cultivate novel competitive edges, while concurrently propelling digital transition processes and constructing a cyber-physical national framework. Achieving these objectives necessitates the systematic reconfiguration of energy allocation systems and industrial form upgrading via intelligent technological integration. Secondly, organizational transformation necessitates adopting digitally-enabled operational models. Businesses must holistically balance economic returns with ecological impacts, leveraging advanced digital solutions to strengthen resource optimization mechanisms. Guided by eco-innovation principles, this strategic alignment fosters synergistic development between economic growth and environmental stewardship. Concurrently, implementing eco-innovation strategies strengthens organizations' industrial positioning while enabling more effective fulfillment of societal commitments. This dual mechanism facilitates brand value enhancement and amplifies commercial expansion capabilities through sustainable practice integration. In conclusion, organizations must prioritize technology-driven eco-innovation as a strategic pathway toward sustainable economic advancement. This necessitates boosting innovation expenditure and establishing essential frameworks that integrate technological modernization with environmental innovation initiatives.

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