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Digital Transformation, R&D Investment and Green Innovation

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Abstract: Amidst the current wave of scientific and technological advancements and industrial evolution, digital transformation has become a pivotal strategy for sustainable development and maintaining a competitive edge. As a forward-looking and sustainable development paradigm, green innovation increasingly highlights its key role in helping enterprises to reduce environmental pollution, maximize the efficacy of resource deployment and management, and achieve the win-win goals of economy and environmental protection. This research scrutinizes the impact and implications of digital transformation on green innovation by analyzing data selected from A-share listed firms from 2010 to 2023. Concurrently, the intermediary function of R&D expenditure is explored. The outcomes reveal that digital transformation exerts a markedly beneficial consequences on corporate green innovation, and this impact is partially channeled through its influence on R&D investment. Furthermore, the catalytic effect of digital transformation on green innovation is more pronounced in publicly-held corporate entities & government-operated institutions, non-polluting industries, and high-technology sectors.

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

1. Introduction

As the pace of the ongoing global technological and scientific revolution and industrial evolution accelerates, enterprises increasingly face the fierce market competition and severe environmental tests. In this context, digital transformation has emerged as a pivotal strategic enabler for organizations to enhance their market competitiveness and achieve long-term sustainable growth. Simultaneously, green innovation, as a forward-looking paradigm of sustainable development, is increasingly highlighting its key role in helping enterprises to reduce environmental pollution, improve resource utilization efficiency, and attain mutually beneficial outcomes for economic growth and environmental sustainability.

Digital transformation implies the process of collecting, processing, cleaning, classifying, categorizing, indexing, mining and analyzing multidimensional and multi-source, massive heterogeneous resources both internally and externally with the help of advanced information technology, so as to achieve business process reengineering, improve organizational effectiveness and create new value. The core of digital transformation lies in a paradigm shift that maximizes the potential of technological and data-driven elements, re-configure operational mechanisms and institutional business processes innovations[1]. This process enables companies to better collect, analyze and utilize data, optimize resource allocation and reduce production costs.

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Green innovation is to take the coordinated development of economy and society, ecological environment and human being as the highest goal of technological innovation. It not only meets the current needs of sustainable social development, but also improves the economic efficiency of enterprises and reduces their environmental risks. Digital transformation also gives rise to new business models and innovation pathways, providing a strong impetus for high-quality economic development and green sustainable development. According to Feng Guo, digital transformation in corporate entities significantly amplifies both the productivity and qualitative advancement of green innovations[2]; Dengchun Jiang suggested that by improving access to capital and market visibility, digital transformation can effectively promote enterprise green innovation, and concurrently, through financial marketization effect can reduce the agency cost, ease the financing constraints, and improve the R & D investment, which further contributes to digital transformation of green innovation effect serves as a constructive moderating factor[3].

At present, the research on green innovation and digital transformation has gradually increased, but the empirical research of both relationship is still insufficient, especially in the aspects of theory construction and empirical analysis, there is a large research space. Therefore, this paper aims to use listed companies as samples during 13 years from 2010 to explore the influence of digital transformation on green innovation in depth, and to reveal the correlation between digital transformation and green innovation through the mediating variable - R&D investment.

2. Theoretical analysis and research hypotheses

There is a profound connection between green innovation and digital transformation. Companies embracing digital transformation could substantially lessen information asymmetry and propel the development of green innovation. In the wave of digital transformation, companies use advanced information technology, which not only improves operational efficiency and innovation ability, but also stimulates innovation vitality, which thereby promotes the development of green innovation. It is also found that digital transformation can promote enterprise green innovation through a variety of mechanisms, such as optimizing resource allocation and improving decision-making efficiency[4]. The digital transformation within corporate entities substantially augments their capabilities in fostering green innovation, with a particularly pronounced impact on substantive environmental advancements. From a mechanism standpoint, this process is mediated through enhanced transparency, optimized resource allocation, and advanced technological convergence. By leveraging informational advantages, resource optimization, and technological synergies, corporate digitization establishes a robust foundation for sustainable innovation initiatives[5].

H1: Digital transformation exerts profoundly beneficial influence on corporate green innovation.

R&D investment, as an intrinsic driving force for the improvement of an enterprise's innovation capacity, affects the output capacity of companies' innovation performance. By applying the "R&D-innovation" effect mechanism, the higher extent of digital transformation, the stronger the effect of R&D investment about improvement of enterprise innovation capability. Digital transformation constantly promotes industrial change, in order to improve product competitiveness, enterprises need to continuously develop new technologies and new applications, and R&D investment is conducive to promoting new knowledge generation, which in turn improves the enterprise's innovation capacity[6].

Drawing upon the aforementioned theoretical framework, the present study posits the following research hypotheses:

H2: Digital transformation positively affects firms' green innovation by increasing firms' R&D investment.

This investigation utilizes quantitative research methods to examine the correlation between organizational digital transformation and green innovation through the collection and analysis of

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extensive enterprise-level data, and use the statistical method and econometric model to deeply explore the consequences of digital transformation on green innovation and its functioning mechanism. Through empirical analysis, This study aims to offer valuable conceptual frameworks and actionable insights for organizational digital transformation and green innovation.

3. Model building

3.1. Data sources

The study focuses on A-share listed companies in the period of 13 years from 2010. To ensure the robustness of findings, several steps were taken: (1) exclusion of ST or PT status companies; (2) removal of all financial firms; (3) elimination of companies with irregular financial data; (4) exclusion of firms with incomplete variable data. Financial data were sourced from the Cathay Pacific CSMAR database, and continuous variables were winsorized at the 1% and 99% levels.

3.2. Model setup

To assess the impact of digital transformation on corporate green innovation and the role of R&D investment in enhancing this relationship, the study employs a model where green innovation is the dependent variable and digital transformation is the independent variable:

$$GI_{it} = \beta_0 + \beta_1 Dig_{it} + \beta_{it} Controls_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (1)$$

Subscript i denotes firm, t is time, GI_{it} denotes green innovation of firm i during the period t, Dig_{it} means the extent of digital transformation of firm i during the period t, $Control_{it}$ implies control variables, μ_i and γ_t are the time and industry fixed effects respectively, and $\varepsilon_{it}$is the stochastic error component. In light of the preceding theoretical examination, H1 is validated provided the coefficient of Dig_{it} β_1 is statistical significance with a positive directionality.

$$GI_{it} = \beta_0 + \beta_1 Dig_{it} + \beta_{it} Controls_{it} + \beta_2 RDS_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (2)$$

To conduct a more rigorous examination of the potential correlation between corporate digitalization and the advancement of sustainable innovation capabilities within business entities through increasing R&D investment (H2) ,model 2 is constructed on the above model with reference to the mediation effect test procedure. RDS_{it}denotes the R&D investment of enterprise i during the period t. According to aforementioned theoretical analysis, if the coefficient of β_2 of RDS_{it} is positively correlated, then H2 is verified.

3.3. Selection of variables

Green innovation (Gi) serves as the dependent variable. Corporate innovation is typically evaluated through two approaches: examining technological and human resource inputs[7] or analyzing the quantity of innovation patents[8][9]. This study measures green innovation by the number of green patent applications, encompassing both green invention and utility model patents, calculated as the sum of independently filed green inventions and utility models in the current year plus one[10].

Digital transformation (Dig) is the explanatory variable. Assessing digital transformation is a complex process that involves various financial and managerial indicators. Following some approaches, this study measures digitization by the proportion of digital transformation-related intangible assets disclosed in the financial reports' notes to the total intangible assets[11].

Based on prior research, the control variables in this study include: leverage ratio (Lev), firm size (Size), net profit margin on total assets (Roa), return on equity (Roe), total asset turnover (Ato), cash

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flow ratio (Cash), inventory ratio (Inv), fixed asset ratio (Fixed), revenue growth rate (Growth), number of directors (Board), and proportion of independent directors (Indep).

The mediating variable is R&D investment (RDS). R&D investment underpins technological innovation, enabling firms to achieve economies of scale and fostering agglomeration economies, which drive economic growth[12]. Increased R&D spending allows companies to develop new technologies, products, and services to meet market demands. As a critical driver of green innovation, R&D investment is measured by the amount spent on R&D, serving as a mediator in the relationship between digital transformation and green innovation.

Table 1: Definition of variables.

variant	variable name	notation	Variable Definition
Explained variable	Green Innovation	Gi	Number of green patent applications
Explanatory variable	Digital Transformation	Dig	The relative composition ratio of digital-oriented elements in the intangible asset portfolio, as delineated in the financial statement footnotes, relative to the aggregate intangible asset valuation.
Intermediary variable	R&D investment	RDS	Logarithmic value of R&D investment
Control variable	Enterprise size	Size	Natural logarithm of total assets
	Net profit margin on total assets	Roa	Net profit/total assets
	gearing	Lev	Total liabilities/total assets
	return on net assets	Roe	Ratio of net profit to net assets at the end of the period
	Total asset turnover	Ato	Operating income/average total assets
	Cash flow ratio	Cash	Net cash flows from operating activities divided by total assets
	Inventory as a percentage	Inv	Ratio of net inventory to total assets
	Fixed assets as a percentage	Fixed	Net fixed assets to total assets
	Revenue growth rate	Growth	Current year's operating income/previous year's operating income - 1
	Is there a loss	Loss	Net profit for the year is less than 0 take 1, otherwise take 0
	Size of directors	Board	The count of executive board participants is subjected to natural logarithmic conversion
	Percentage of independent directors	Indep	Independent directors divided by number of directors
	two jobs in one	Dual	The chairman of the board and the general manager are the same person as l, otherwise 0

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3.4. Descriptive statistics

Table 1 summarizes the fundamental statistical characteristics of the key variables incorporated in the primary regression model.

Table 2: Descriptive statistics.

Variable	N	mean	sd	min	p50	max
Dig	31865	0.0900	0.210	0	0.0100	1
Gi	31857	0.350	0.750	0	0	3.560
Gi3	31836	0.230	0.600	0	0	3.090
Lev	31865	0.420	0.200	0.0600	0.410	0.870
Size	31865	22.17	1.260	19.96	21.99	26.04
Roa	31865	0.0400	0.0600	-0.190	0.0400	0.210
Roe	31865	0.0700	0.120	-0.480	0.0700	0.330
Ato	31865	0.650	0.420	0.0900	0.550	2.390
Cash	31865	0.0500	0.0700	-0.150	0.0500	0.230
Inv	31850	0.140	0.130	0	0.110	0.650
Fixed	31865	0.210	0.150	0	0.180	0.670
Growth	31865	0.170	0.350	-0.490	0.110	1.900
Board	31835	2.120	0.200	1.610	2.200	2.640
Indep	31835	37.57	5.310	33.33	36.36	57.14
RDS	26799	17.91	1.480	13.71	17.90	21.89
Dual	31865	0.280	0.450	0	0	1
Loss	31865	0.100	0.310	0	0	1

4. Empirical analysis

4.1. Analysis of baseline results

Model (1) was used to test Hypothesis 1, with results displayed in Table 3. The coefficient for digital transformation (Dig) is 0.0540, statistically significant at the 1% level ($p<0.01$), demonstrating a robust and statistically significant positive correlation on corporate green innovation. This supports H1, suggesting that corporations exhibiting deeper digital transformation maturity demonstrate a greater tendency to prioritize resource allocation for green innovation.

After incorporating control variables, the regression coefficients for inventory ratio, fixed assets ratio, and revenue growth rate are significantly negative, suggesting that firms with high inventory and fixed asset ratios, as well as strong growth potential, exhibit lower levels of green innovation. The high absolute values of these coefficients highlight the pronounced impact on green innovation.

Table 3: Benchmark regression results, robustness test results, Mediation effect regression results for R&D investment.

	(1)	(2)	(3)	(4)
	Gi	Gi3	RDS	Gi
Dig	0.0540***	0.0548***	0.172***	0.0509**
	(0.0206)	(0.0166)	(0.0318)	(0.0255)
Lev	0.128***	0.0640***	-0.734***	0.238***
	(0.0285)	(0.0229)	(0.0417)	(0.0336)
Controls	√	√	√	√

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Table 3: (continued).

Year	√	√	√	√
Ind	√	√	√	√
RDS				0.110 ***
				(0.00490)
_cons	-3.163 ***	-2.753 ***	-3.288 ***	-3.076 ***
	(0.170)	(0.0943)	(0.150)	(0.121)
N	31812	31791	26785	26777
R^2	0.186	0.166	0.638	0.188
adj. R^2	0.183	0.163	0.636	0.185

Note: ***, **, * mean significant at 1%, 5%, 10% level respectively, robust standard errors in parentheses, same table below.

4.2. Intermediary effect

To examine whether digital transformation influences green innovation through R&D investment as the mediating variable, a regression analysis was conducted which is presented in Table3. Column (3) reveals that digital transformation coefficient is 0.172, significant at the 1% level, which means higher digital transformation levels facilitate access to financial and resource support for R&D. Column (4) shows a coefficient of 0.0509 for R&D investment, significant at the 5% level, demonstrating that increased R&D spending enhances innovation resources, thereby boosting green innovation. These findings confirm H2, demonstrating that digital transformation positively impacts green innovation by increasing R&D investment.

4.3. Robustness check

The robustness test is used to examine the robustness of the explanatory power of some indicators, that is the stability and reliability of evaluation frameworks and their corresponding indicators in preserving result interpretation consistency under different parametric conditions. In the benchmark regression, green innovation (Gi) is measured by number of green patent applications. To test robustness, the dependent variable was changed by green utility models number in the year plus one (Gi3), and model (1) was re-estimated. Column (2) of Table 3 shows a coefficient of 0.0548 for digital transformation, which still remains significant and shows digital transformation continues to drive green innovation even with the altered measurement. This confirms the robustness of the study's findings.

4.4. Endogeneity test

To make sure the reliability and validity of outcomes, the study employed propensity score matching to address endogeneity. The sample was divided into treatment and control groups based on whether firms exceeded the median level of green innovation. The regression analysis was repeated on the matched samples, and the coefficients remained significantly positive, supporting the study's conclusions.

4.5. Heterogeneity test

4.5.1. Heterogeneity analysis of the nature of property rights

To investigate the moderating effect of companies ownership structure on the relationship between digital transformation and green innovation, we stratified the sample into two distinct cohorts according to their ownership characteristics: state-controlled enterprises and privately-held entities.

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Separate regression analyses were conducted for each subgroup, with the comprehensive findings meticulously presented in columns (1) and (2) of Table 4. For state-owned enterprises (SOEs), the coefficient for digital transformation is significantly positive at the 5% level, whereas for non-SOEs, the impact is merely positive. This indicates that digital transformation has a more pronounced impact on green innovation in SOEs compared to non-SOEs.

SOEs benefit from greater government policy support and guidance in digital transformation, providing them with a competitive edge in both digital transformation and green innovation. Additionally, their robust foundations and scale advantages facilitate access to innovation resources, which further drives digital transformation and enhances green innovation capabilities.

Table 4: Results of the analysis of heterogeneity in the nature of ownership structure.

	(1)	(2)	(3)	(4)	(5)	(6)
	Gi	Gi	Gi	Gi	Gi	Gi
Dig	0.0905**	0.0185	0.0402	0.0609**	0.0757**	0.0109
	(0.0373)	(0.0245)	(0.0395)	(0.0242)	(0.0319)	(0.0217)
Lev	0.0337	0.185 ***	0.110**	0.134 ***	0.254 ***	-0.132 ***
	(0.0490)	(0.0356)	(0.0535)	(0.0339)	(0.0419)	(0.0324)
Controls			√			
Year			√			
Ind			√			
_cons	-3.450 ***	-2.563***	-3.520 ***	-2.965 ***	-4.750 ***	-1.175 ***
	(0.231)	(0.283)	(0.325)	(0.202)	(0.277)	(0.164)
N	11534	20278	9658	22154	19226	12586
R^2	0.245	0.177	0.213	0.183	0.159	0.253
adj. R^2	0.238	0.173	0.204	0.179	0.157	0.247

4.5.2. Heterogeneity analysis of the nature of the contamination

The development of heavily polluted industries is more likely to bring about environmental pollution problems, and the implementation of environmentally sustainable innovation initiatives presents greater challenges for enterprises operating within high-pollution industrial sectors. The degree of pollution of different enterprises will also exert an influence on the development of green innovation of companies. To verify what kind of impact heavy polluting and non-heavily polluting companies will have on the extent to which green innovation has evolved, the subsequent analytical procedure involves stratifying the sample population into two distinct cohorts of heavy pollution and non-heavily polluting and carries out a group regression and Table 4 presents the results. For non-heavily polluting firms, the coefficient for digital transformation is 0.0609, significant at the 5% level, whereas for heavily polluting firms, the coefficient is 0.0402 and not significant. This suggests that digital transformation exerts a more pronounced beneficial influence on green innovation in less polluting industries.

Non-heavily polluting business enterprises face relatively less environmental pressure and green transformation pressure, so they can devote more resources and energy to digital transformation and are more likely to achieve a breakthrough. Because their initial pollution level is lower, they can more easily achieve green innovation by optimizing their enterprise structure through digital transformation, improving the efficiency of resource utilization, and rationally planning green development strategies. On the other hand, heavily polluting corporate enterprises usually face tougher pollution control requirements, stricter social supervision and greater pressure for green transformation. This may lead

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them to keep more eyes on pollution control in the short term during the digital transformation process and neglect their long-term green innovation development strategies.

4.5.3. Heterogeneity analysis of the nature of science and technology

The degree of scientific and technological development of different enterprises will also have an impact on green innovation development, in order to verify whether high technology enterprises and non-high-tech enterprises have an impact about the level of green innovation development, the sample is stratified into high-tech and non-high-tech categories and grouped regression, and the specific results of the analysis about science and technology heterogeneity are presented in Table 4. Columns (5) and (6) show the outcomes for high-tech & non-high-tech firms, respectively. The regression analysis for high-technology enterprises yields a digital transformation coefficient of 0.0757, demonstrating statistical significance at the 95% confidence level ($p < 0.05$), while the coefficient of digital transformation in the regression outcomes of the non-high-tech subgroup is 0.0109 and insignificant, compared to which the positive outcome of digital transformation on green innovation is even more marked salutary in high-tech companies.

High-tech enterprises usually have a more advanced and mature technological base, which provides strong technological support for digital transformation, enabling high-tech enterprises to advance the digitization process more quickly and efficiently. Non-high-tech enterprises have relatively weak technological foundations, lack the necessary technical support and talent reserves, and have weaker innovation capabilities, posing significant challenges for their ability to quickly adapt and apply new technologies for green innovation. Instead, high-tech enterprises are able to carry out digital transformation more efficiently, thereby promoting green innovation development.

5. Conclusion

5.1. Conclusions of the study

This paper analyzes the relevant data of China's A-share listed companies from 2010 to 2023 to study the relationship between digital transformation, R&D investment and green innovation, and at the same time analyzes how R&D investment plays a key role between the two, thus proposing two core hypotheses and verifying them through empirical analysis. The outcomes show that digital transformation helps to promote the progress of green innovation, while R&D investment plays an important mediating role in it.

5.2. Policy recommendations

Corporate entities should comprehensively acknowledge the pivotal significance of digital transformation in catalyzing sustainable innovation initiatives. Through strategic investments in cutting-edge information technologies, including advanced data analytic and machine learning systems, organizations can enhance their internal governance frameworks and operational efficiency, thereby allocating greater resources and institutional support toward environmentally-conscious innovation endeavors.

R&D expenditure serves as a pivotal intermediary factor connecting digital transformation with green innovation. Companies should raise R&D investment, cultivate R&D talents, strengthen R&D and application of green technologies, as well as promote the innovative progress of green products. During the progression of digital transformation, companies should allocate resources judiciously to cater to the demands of both digital evolution and green innovation, thereby fostering sustainable enterprise development. Firms varying in ownership structure, pollution intensity, and technological proficiency exhibit distinct impacts from digital transformation on green innovation. Consequently,

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enterprises ought to devise a tailored strategy for digital transformation and green innovation that aligns with their unique attributes.

The administrative sector needs to devise strategic initiatives to promote industrial players to carry out digital transformation and green innovation, and at the same time establish a sound innovation system to provide comprehensive technical support and services to enterprises. The government should formulate and improve regulations and standards related to digital transformation and green innovation to guide enterprises to develop in compliance. Simultaneously, it is imperative to foster synergistic growth across diverse industrial sectors, enhance collaboration and interaction between enterprises occupying distinct segments within the supply chain hierarchy, and catalyze the dissemination and permeation of digital transformation and green innovation throughout the industrial landscape.

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