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The Impact of Digital Economy on Enterprises' Green Technological Innovation

Limei Fu, Duorijie Zhuoma

Hainan Vocational University of Science and Technology, Hainan, China

Abstract: Against the backdrop of the coordinated advancement of Digital China construction and the dual carbon goals, exploring the enabling effect of the digital economy on the green transformation of micro-enterprises is of great theoretical and practical significance. Based on the resource-based view and information asymmetry theory, this paper takes China's Shanghai and Shenzhen A-share listed companies from 2013 to 2023 as research samples and constructs an enterprise digital economy development index. Adopting a two-way fixed effect model, this paper empirically examines the impact of the digital economy on corporate green technological innovation. The research results show that the digital economy can significantly promote enterprises' green technological innovation, and the conclusion remains valid after a series of robustness tests including substituting explained variables, lagging core explanatory variables, and Tobit model regression. Heterogeneity analysis indicates that the driving effect of the digital economy is more prominent in non-state-owned enterprises and heavily polluting industries. Mechanistically, the digital economy alleviates information asymmetry and financing constraints, thereby stimulating green R&D investment and innovation output. This paper finally puts forward targeted policy suggestions on improving digital infrastructure, implementing differentiated incentive policies, and promoting the integration of digital and real economies, which provides empirical evidence for the coordinated realization of high-quality economic development and ecological environmental improvement.

Keywords: Digital economy; Green technological innovation; Enterprise heterogeneity; Two-way fixed effect model

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1. Introduction

The new round of technological revolution represented by emerging digital technologies is driving the global economic transformation into a digital economy era. As a strategic pillar for China to seize new technological development opportunities and achieve high-quality economic growth, the digital economy has become a core force for restructuring global factor allocation and reshaping the international economic pattern. The report of the 20th National Congress of the Communist Party of China emphasizes accelerating the development of the digital economy and deepening the integration of digital technology and the real economy. Digital technologies such as big data, cloud computing and artificial intelligence have evolved from auxiliary tools to leading driving

forces for industrial transformation, creating innovative technological paths and development models for the green upgrading of traditional industries.

Meanwhile, green development has become the fundamental keynote of China's economic growth under the constraints of resource scarcity and global climate change. Since the proposal of the dual carbon goals, China's economic development model has been transforming from the extensive growth characterized by high energy consumption and high emissions to an intensive green and low-carbon development mode. As major micro-economic entities, enterprises' green technological innovation capabilities are crucial for promoting comprehensive green transformation of the economy and society. However, green technological innovation features significant double externalities, high costs, long cycles, and high risks. Most enterprises face problems such as insufficient innovation enthusiasm, unreasonable resource allocation, and financing shortages in green technological upgrading, which hinder their green transformation process. Therefore, external driving forces are urgently needed to solve the above dilemmas.

Against this background, the coordinated development of digitalization and greening has become a core focus of policy formulation and academic research. The 14th Five-Year Plan for Digital Economy Development clearly proposes empowering the energy conservation and emission reduction of traditional industries through digital technology and promoting production mode transformation via digital upgrading. With the characteristics of high innovation, strong permeability, and wide coverage, the digital economy can optimize resource allocation and eliminate information asymmetry, which provides an effective solution for enterprises' green innovation dilemmas. Accordingly, exploring the impact and internal mechanism of the digital economy on corporate green technological innovation is not only in line with China's major national strategies, but also provides valuable practical references for micro-enterprises to realize green and high-quality development in the digital era.

2. Literature review

2.1. The impact of digital economy on corporate green technological innovation

Multidimensional empirical studies by domestic scholars have demonstrated that the digital economy exerts a significantly positive impact on enterprises' green technological innovation. Specifically, Ni *et al.* conducted an empirical analysis using the difference-in-differences (DID) model. Their findings reveal that a 1% increase in the development level of the digital economy leads to a notable 0.8% rise in enterprises' green patent applications. Numerous other domestic scholars have carried out empirical research from diverse perspectives and reached analogous conclusions: the advancement of the digital economy stimulates enterprises to engage in more green technological innovation activities. Furthermore, this facilitating effect is more pronounced in strategic emerging industries [9].

Taking the "Broadband China" initiative as a quasi-natural experiment, Wang and Gao found that the development of digital economic infrastructure in pilot cities elevates enterprises' green technological innovation levels by approximately 12.6%, thereby verifying the enabling effect of digital infrastructure on green innovation [11]. Li and Deng argued that the digital economy helps address enterprises' bottlenecks in green innovation and constructs an indirect transmission path through which the digital economy influences corporate green technological innovation [14]. Long distinguished between two forms of the digital economy and posited that industrial digitalization imposes a stronger and longer-lasting influence on green technological

innovation than digital industrialization [13]. Li *et al.* discovered that integrating the digital economy with innovation policies boosts enterprises' green innovation efficiency by 15.3%, with this synergistic effect standing out more prominently in technology-intensive industries.

Overall, existing domestic research primarily explores the direct impacts, intermediate transmission mechanisms, heterogeneous effects, and policy coordination of the digital economy on corporate green technological innovation, fully confirming that digital economic development actively drives enterprises' green technological innovation. This body of literature lays a solid theoretical and documentary foundation for the present study [10].

2.2. Digital economy boosts China's economic transformation and high-quality development

Extant literature mainly adopts macro and meso perspectives to investigate the impacts of digital economic development on green total factor productivity, green ecological efficiency, pollutant gas emissions and other dimensions, and generally confirms that the digital economy significantly facilitates green development at the regional and industrial levels.

For instance, based on provincial panel data, Yang empirically verified that digital economic development improves green total factor productivity, chiefly by stimulating technological research and development and optimizing energy consumption patterns [1]. Ji examined urban digital economic development and found that the digital economy enhances green ecological efficiency by raising industrial concentration and optimizing industrial structures [2]. Yu and He pointed out that digital technologies substantially cut emissions of industrial sulfur dioxide, nitrogen oxides, and other pollutants, especially in central and western China [3]. Analyzing regional green economic efficiency, Li *et al.* confirmed that the digital economy remarkably fuels the growth of regional green economic efficiency by mitigating factor misallocation and improving resource allocation efficiency [5].

From the perspective of digital finance, Shu and Huang found that digital finance indirectly upgrades regional green technological standards by easing corporate financing constraints [6]. Zhou and He illustrated that the digital economy not only directly advances regional green development but also reduces carbon emission intensity via the mediating effect of green technological innovation [7].

Nevertheless, most of the above studies adopt macro or meso-level analyses targeting provinces, cities, or industries. Although they identify the green development-promoting effect of the digital economy, they fail to elaborate on how digital technologies specifically shape enterprises' green technological innovation. In contrast, research examining the nexus between the digital economy and corporate green technological innovation from a micro-firm perspective lacks systematic empirical evidence. In particular, the intrinsic correlations among corporate digital input intensity, digital transformation depth, and micro-level green innovation output remain underexplored. Accordingly, this study adopts a micro enterprise perspective and utilizes listed firm data to examine the digital economy's impact on green technological innovation as well as heterogeneous effects, with the aim of filling gaps in existing research.

While prior literature provides a robust theoretical framework for this study, there remains room for further refinement. First, most studies measure digital economic development via composite index methods. Due to the wide array of internal constituent indicators and inconsistent statistical standards across regions, this approach suffers from subjective indicator selection and limited data availability, resulting in inconsistent research conclusions. Second, existing research predominantly focuses on the overall impact of the digital economy on

green technological innovation, with fragmented discussions on heterogeneous effects; systematic examinations of differentiated impacts across industries and firm size categories are particularly scarce. Building on prior research achievements, this paper combines documentary analysis and empirical methods to investigate heterogeneous effects, identifying research gaps and supplementing deficiencies in existing literature so as to better support governmental decision-making and theoretical advancement.

2.3. Research gaps

Current studies have formed a basic theoretical framework for the digital economy and green innovation, but there are still deficiencies to be supplemented. First, most studies adopt comprehensive index methods to measure the digital economy, with strong subjectivity in index selection and inconsistent statistical standards, leading to inconsistent research conclusions. Second, existing literature focuses more on the overall impact of the digital economy on green innovation, while the discussion of enterprise and industrial heterogeneity is scattered and unsystematic. This study conducts systematic empirical tests on micro-level enterprise data to make up for the above research deficiencies.

3. Theoretical analysis and research hypotheses

3.1. Digital economy and corporate green technological innovation

Centered on data elements and digital technologies, the digital economy accelerates the efficient flow and optimal allocation of innovation resources such as knowledge, technology, and capital. Supported by big data and cloud computing, enterprises can accurately identify green market demands and reduce R&D uncertainty and innovation trial-and-error costs. Digital platforms optimize R&D processes and shorten the innovation cycle of green technologies. Furthermore, the digital economy improves information transparency, alleviates information asymmetry between enterprises and financial institutions, enhances enterprises' access to green credit and government policy support, eases financing constraints for high-risk green innovation projects, and ultimately boosts corporate green technological innovation capabilities. Accordingly, this paper proposes the first hypothesis:

H1: The development of the digital economy significantly promotes enterprises' green technological innovation.

3.2. Heterogeneity of property rights

Under China's unique institutional background, enterprises with different property rights differ greatly in resource acquisition capacity and operation objectives. State-owned enterprises (SOEs) enjoy government endorsement, convenient credit resources and policy support, and face fewer capital shortages in green innovation. Meanwhile, SOEs undertake more political and social responsibilities for green transformation. In contrast, non-state-owned enterprises (non-SOEs) have long been plagued by financing difficulties and high financing costs, and resource scarcity is the core obstacle to their high-risk green innovation activities.

The development of the digital economy constructs a digital credit evaluation system, effectively making up for the credit disadvantages of non-SOEs in the traditional financial system, reducing their financing thresholds and costs, and providing stable financial support for green R&D. Therefore, the resource optimization effect of the digital economy on non-SOEs is more significant. Based on the above analysis, the second hypothesis is proposed:

H2: The digital economy exerts a more significant promoting effect on green technological innovation in non-state-owned enterprises than in state-owned enterprises.

3.3. Heterogeneity of industry types

Industries vary significantly in environmental sensitivity and regulatory intensity, resulting in differentiated demands for digital transformation and green innovation. Heavily polluting industries are the key supervision objects of environmental regulation, facing stringent environmental compliance constraints and urgent green transformation pressure. Digital technology enables full-process energy consumption monitoring and pollutant emission control for enterprises in heavily polluting industries, helping them improve production efficiency, meet regulatory requirements, and achieve rapid energy conservation and emission reduction with remarkable transformation effects.

On the contrary, non-heavily polluting industries bear lower environmental governance pressure, with insufficient internal and external driving forces for digital green innovation. Therefore, the empowering effect of the digital economy on green technological innovation is more prominent in heavily polluting industries. The third hypothesis is proposed accordingly:

H3: The digital economy has a stronger promoting effect on green technological innovation of enterprises in heavily polluting industries than in non-heavily polluting industries.

4. Research design

4.1. Variable definition and measurement

The definitions and measurement methods of core and control variables in this paper are shown in **Table 1**.

Table 1. Definition and measurement of main variables

Variable type	Variable name	Symbol	Measurement method
Explained Variable	Green Technological Innovation	GTI	Natural logarithm of (the number of listed companies' annual green patent applications + 1)
Core Explanatory Variable	Digital Economy Development	DigEcon	Natural logarithm of (the total frequency of digital-related keywords in annual reports + 1)
Control Variable	Enterprise Size	Size	Natural logarithm of year-end total assets
	Asset-Liability Ratio	Lev	Year-end total liabilities / year-end total assets
	Return on Assets	ROA	Net profit / average year-end total assets
	Enterprise Age	Age	Natural logarithm of (current year - establishment year + 1)
	Dual Leadership	Dual	Dummy variable; 1 if the chairman concurrently serves as general manager, otherwise 0
	Board Size	Board	Natural logarithm of the number of board members
	Cash Flow Ratio	Cashflow	Net cash flow from operating activities / year-end total assets

4.2. Model construction

To verify the research hypotheses, this paper constructs a two-way fixed effect model to test the direct impact of the digital economy on corporate green technological innovation:

$$GTI_{i,t} = \alpha_0 + \alpha_1 DigEcon_{i,t} + \sum \gamma_k Controls_{i,t} + \delta_j + \lambda_t + \varepsilon_{i,t}$$

Where *i* represents the enterprise, *t* represents the year, and *j* represents the industry. *GTIi,t* denotes the green technological innovation level of enterprise *i* in year *t*; *DigEconi,t* is the core explanatory variable of digital economy development; *Controls* represents the set of control variables; δj denotes industry fixed effects; λt denotes year fixed effects; εi,t is the random disturbance term. If α is significantly positive, it indicates that the digital economy significantly promotes corporate green technological innovation, which verifies H1.

4.3. Sample selection and data sources

This paper selects China's Shanghai and Shenzhen A-share listed companies from 2013 to 2023 as the research samples. The year 2013 is selected as the starting point because digital economy concepts and technological applications were gradually reflected in listed companies' annual reports during this period, and China's green development policy system was increasingly improved, ensuring good research representativeness. This study eliminates ST, *ST, and financial enterprises with severe missing data, and finally obtains 12,480 firm-year observations. All empirical data are derived from the China Stock Market & Accounting Research Database (CSMAR).

5. Empirical results and analysis

5.1. Descriptive statistics

The descriptive statistical results of the main variables are shown in **Table 2**. The mean value of corporate green technological innovation (GTI) is 0.854 with a standard deviation of 1.127, indicating that the green innovation level of listed companies in China is generally low with obvious inter-enterprise differences. The mean value of digital economy development (DigEcon) is 3.215, and the large standard deviation and extreme value difference reflect significant unbalanced digital development among sample enterprises. All control variables are reasonably distributed without abnormal values, and the sample has good heterogeneity, which meets the requirements of large-sample empirical research and supports subsequent regression analysis.

Table 2. Descriptive statistics of main variables

Variable	N	Mean	Std.Dev	Min	Max
GTI	12480	0.854	1.127	0.000	5.684
DigEcon	12480	3.215	1.453	0.042	6.891
Size	12480	22.450	1.320	19.850	26.780
Lev	12480	0.432	0.205	0.054	0.892
ROA	12480	0.038	0.065	-0.254	0.225
Age	12480	2.854	0.352	1.099	3.611
Dual	12480	0.285	0.451	0.000	1.000
Board	12480	2.156	0.187	1.609	2.708
Cashflow	12480	0.049	0.072	-0.158	0.261

5.2. Correlation analysis

Pearson correlation test results show that the correlation coefficient between digital economy development and corporate green technological innovation is 0.158, which is significantly positive at the 1% level, initially verifying the research hypothesis of this paper. In terms of control variables, enterprise size and profitability

are significantly positively correlated with green innovation, while asset-liability ratio shows a significant negative correlation, which is consistent with existing theoretical research. In addition, the absolute values of correlation coefficients between all core variables are lower than the critical value of 0.7, indicating no serious multicollinearity problem. The model setting is reasonable and suitable for further regression analysis.

5.3. Benchmark regression analysis

The benchmark regression results are presented in **Table 3**. Column (1) shows the regression results without control variables, and Column (2) adds all control variables on the basis of fixed effects. After incorporating control variables, the adjusted goodness of fit (Adj.R^2) increases from 0.045 to 0.128, indicating improved model explanatory power. The regression coefficient of the digital economy remains significantly positive at the 1% level (coefficient = 0.118), which indicates that digital economy development effectively promotes corporate green technological innovation, fully verifying H1.

For control variables, enterprise size and profitability significantly boost green innovation, consistent with the Schumpeter hypothesis that large-scale and high-profit enterprises have stronger R&D and innovation capabilities. Asset-liability ratio is significantly negative, implying that excessive debt pressure squeezes green R&D investment and inhibits green innovation. All control variables have reasonable economic implications and robust regression results.

Table 3. Benchmark regression results

Variable	(1) GTI	(2) GTI
DigEcon	0.142***	0.118***
Size	-	0.156***
Lev	-	-0.210**
ROA	-	0.482***
Age	-	0.054
Dual	-	-0.021
Board	-	0.098*
Constant	-0.452***	-3.125***
Year FE	YES	YES
Industry FE	YES	YES
N	12480	12480
Adj.R^2	0.045	0.128

Note: ***, **, * denote significance at the 1%, 5%, and 10% levels respectively.

5.4. Heterogeneity analysis

5.4.1. Heterogeneity of property rights

This paper divides the sample into state-owned enterprises and non-state-owned enterprises for grouped regression. The results show that the digital economy significantly promotes green technological innovation in both types of enterprises, but the coefficient of non-state-owned enterprises (0.135) is significantly higher than that of state-owned enterprises (0.092), and the inter-group coefficient difference test is significant.

State-owned enterprises have stable government support and convenient credit resources, with fewer financing constraints in green innovation. In contrast, non-state-owned enterprises face long-term financing

difficulties. The digital economy effectively alleviates information asymmetry, reduces the financing threshold of non-state-owned enterprises, and makes up for their resource deficiencies in green R&D. Therefore, the marginal driving effect of the digital economy on green innovation is more prominent in non-state-owned enterprises, which verifies H2.

5.4.2. Heterogeneity of industry types

According to industrial environmental regulation intensity, the sample is divided into heavily polluting industries and non-heavily polluting industries. The regression results indicate that the digital economy has a significant positive impact on green innovation in both industries, while the promoting effect on heavily polluting industries (coefficient = 0.158) is obviously stronger than that of non-heavily polluting industries (coefficient = 0.076).

Heavily polluting industries are key targets of environmental supervision, facing severe compliance pressure and urgent green transformation demands. Digital technology realizes precise monitoring of energy consumption and pollutant emissions, helping such enterprises achieve efficient green upgrading with remarkable and rapid energy-saving effects. Non-heavily polluting industries have low environmental governance pressure and insufficient internal and external motivation for digital green innovation. Thus, the empowering effect of the digital economy is more significant in heavily polluting industries, which supports H3.

5.5. Robustness tests

To eliminate the interference of measurement errors and endogeneity problems, this paper conducts robustness tests through three methods: substituting explained variables, lagging core explanatory variables, and Tobit model regression.

First, replacing the explained variable with green patent granted quantity, the digital economy coefficient remains significantly positive at the 1% level. Second, after lagging the core explanatory variable by one period to alleviate endogeneity bias, the lagged digital economy still significantly promotes green innovation, confirming the long-term continuity of the driving effect. Third, considering the truncated characteristics of green innovation data, the Tobit model is adopted for re-estimation, and the core conclusion remains stable. The above tests fully verify the robustness and reliability of the benchmark regression results.

6. Conclusion and policy implications

6.1. Research conclusions

Based on the panel data of China's A-share listed companies from 2013 to 2023, this paper constructs a two-way fixed effect model to explore the impact of the digital economy on corporate green technological innovation. The research conclusions are as follows: First, the digital economy significantly promotes enterprises' green technological innovation, and the conclusion is robust after multiple robustness tests. Second, there is obvious enterprise heterogeneity in the promoting effect: the digital economy plays a stronger role in empowering green innovation of non-state-owned enterprises by alleviating their financing constraints. Third, industrial heterogeneity exists significantly: the driving effect of the digital economy is more prominent in heavily polluting industries, which helps high-pollution enterprises realize digital and green coordinated transformation.

6.2. Policy implications

First, improve digital infrastructure construction to consolidate the foundation of green transformation. The government should increase investment in new digital infrastructure such as 5G base stations, big data centers, and industrial Internet, optimize regional digital resource allocation, and reduce the digital transformation threshold for enterprises, so as to provide solid technical support for corporate green innovation.

Second, implement differentiated incentive policies to improve policy accuracy. Targeted financial subsidies and tax preferential policies should be launched for non-state-owned enterprises to alleviate their financing bottlenecks in green R&D. For heavily polluting industries, while strengthening environmental supervision, the government should guide enterprises to apply digital technologies such as the Internet of Things and digital twins to realize refined energy-saving and emission-reduction management, and promote industrial green upgrading.

Third, deepen the integrated development of digitalization and greening to form a dual driving mechanism. Enterprises should take advantage of digital technology to carry out full lifecycle management of products, optimize production processes, and accurately tap green market demands. Meanwhile, enterprises should cultivate interdisciplinary talents with digital technology and environmental protection knowledge, improve resource allocation efficiency, and transform digital innovation achievements into sustainable green development competitiveness.

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