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DIGITAL TRANSFORMATION, NEW QUALITY PRODUCTIVE FORCE AND GREEN TECHNOLOGY INNOVATION

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Abstract: Using panel data of Shanghai and Shenzhen A-share listed companies from 2012 to 2023 to systematically examine the transmission mechanism among digital transformation, new quality productive force and green technology innovation. Empirical analysis shows: First, accelerating the digital transformation process and improving the level of new quality productive force can significantly enhance the level of green technology innovation; Second, digital transformation contributes to the improvement of new quality productive force; Third, new quality productive force shows a significant mediating effect between digital transformation and green technology innovation. The research results can provide theoretical guidance for enterprises to enhance their green innovation capabilities through digital transformation and new quality productive force, thereby improving their core competitive advantages.
Keywords: New quality productive force; Technological innovation; Green; Digital transformation

1 INTRODUCTION

In view of the continuing deterioration of the ecosystem, increasing environmental pollution and the tightening of resource constraints in China, the Party Central Committee has repeatedly mentioned the importance and urgency of promoting the construction of a green economy. The Fifth Plenary Session of the 16th CPC Central Committee put forward the idea of building a "resource-conserving and environment-friendly society", focusing on the economical use of resources and the protection of natural ecosystems. The new development concept advocated by the Fifth Plenary Session of the 18th CPC Central Committee highlights the element of "green" and actively advocates the harmonious coexistence of man and nature. The report of the 20th Party Congress clearly states that respecting nature, adapting to nature and protecting nature are the fundamental requirements for the comprehensive construction of a modern socialist country, and stresses that a good ecological environment is the most popular form of people's well-being.

Concurrently, digital transformation is profoundly altering the business models and competitive landscapes of enterprises. In view of the aforementioned points, it is important to consider how digital transformation can play a significant role in the innovation of green technology, which is vital for sustainable economic development. Furthermore, the study will explore how this innovation can stimulate the enthusiasm of Chinese enterprises for green technological innovation, and consequently improve the level of green technological innovation in China. The primary objective of this research is to address these issues.

The existing literature presents a multi-theoretical perspective on the driving mechanism of green technology innovation, with the double-edged sword effect of environmental regulation as the core point of contention. The promotion theory posits that reasonable environmental regulations can stimulate the improvement of green technology innovation in enterprises [1-3], while the inhibition theory reveals the crowding-out effect of environmental factors on R&D resources, thereby hindering the development of technology and processes in the production process and thus affecting the green technology innovation of enterprises [4]. More complex is the existence of nonlinear relationships, as Wang Zhenyu et al. [5] argue that there is a "U" -shaped relationship between environmental regulations and corporate green innovation.

Most of the existing studies on the relationship between digital transformation and green technology innovation suggest that there is a significant synergy effect, and the mechanism of action shows multi-dimensional characteristics. From the perspective of factor input, the digitalization process of enterprises forms the resource advantage of green technology innovation by increasing the input of digital resources[6] and the input of R&D elements [7]; From the perspective of organizational change, the upgrading of human capital structure and the construction of a collaborative network among industry, academia and research[8] jointly drive the evolution of the green innovation ecosystem. The moderating effect analysis further reveals that the ecological benefits of digital transformation are significantly enhanced when enterprises possess the following capabilities: human capital capabilities, technology integration capabilities, and technology absorption capabilities [9] , etc.

A comprehensive review of extant literature reveals a predominant consensus among scholars that digital transformation is positively associated with green technological innovation, with a predominant focus on human capital and resource allocation. However, the theoretical value of new quality productive force as the core engine of high-quality development has not yet been fully deconstructed. In particular, there remain significant research gaps concerning the mediating transmission mechanism in the "digital-green" co-evolution. Therefore, this paper places digital transformation, new quality productive force and green technology innovation in a

unified research framework and examines the mechanism of their interaction in depth, which is of great practical significance for promoting the improvement of the level of green technology innovation in enterprises. The possible marginal contribution of this paper lies in: First, expanding the research on digital transformation and green technology innovation on the basis of existing theoretical literature. Second, from the perspective of indirect effects, exploring whether there is an influence channel of "digital transformation - new quality productive force - green technology innovation" to provide a new perspective for studying the impact of digital transformation on green technology innovation.

2 THEORETICAL ANALYSIS AND RESEARCH HYPOTHESES

2.1 The Impact of Digital Transformation on Green Technology Innovation

Digital transformation can be defined as a strategic process in which enterprises integrate digital technology clusters to systematically and digitally restructure their operational architecture, thereby achieving intelligent transformation of production systems and data-driven optimization of management processes[10]. Enterprise green technology innovation refers to the continuous innovation process in the operational system by which enterprises systematically reduce environmental negative externalities and improve resource utilization efficiency through technological innovation, process improvement and product reconfiguration.

Based on the theoretical framework of the dynamic resource base view, the digital transformation of enterprises reconfigures the endowment of innovation resources through the embedding of digital elements, forming the potential of digital resources for green technological innovation. Digital transformation brings new material production factors to enterprises, such as infrastructure and smart networks, helping them to transform their resource capability system and mechanism creation model and acquire green innovation resources more efficiently. Artificial intelligence also plays a unique role in green technology innovation. It can be used to optimize complex production systems to maximize energy efficiency and minimize waste emissions. For example, in the quality control stage of industrial production, AI algorithms can detect product defects quickly and accurately, avoiding resource waste and additional energy consumption due to quality issues. At the same time, AI can also be used to predict equipment failures, schedule maintenance in advance, and reduce excessive energy consumption and possible environmental pollution caused by sudden equipment failures.

Corporate digital transformation for green technology innovation can be achieved by reducing information asymmetry. Digital transformation can promote high transparency and openness of data, thereby facilitating extensive exchange and deep sharing of information both within and outside the enterprise. By building a unified and efficient information interaction platform, enterprises can obtain the latest information on environmentally friendly materials, advanced technologies and specialized equipment from upstream and downstream of the industrial chain in real time, and build a rich information resource pool needed for green technology innovation. This information resource can provide precise innovation guidance for the enterprise's internal R&D team, enabling them to closely align with market demands and industry development trends in the selection, design and implementation of innovation projects, significantly improve the practicality and market conversion rate of innovation results, and accelerate the process of green technology innovation results moving from the laboratory to market application. As a result, the following assumption is proposed:

Hypothesis 1: Digital transformation promotes the improvement of green technology innovation capabilities of enterprises.

2.2 The Impact of New Quality Productive Force on Green Technology Innovation

New quality productive force is a new starting point for high-quality economic growth and a productive force for transforming the traditional growth model and aiming for high-quality development. Compared with traditional productivity, new quality productive force takes innovation-driven development as its core logic, highly gathers innovative elements, involves new industries and new fields, new technologies and new models, and represents a leap and upgrade of productivity [11].

New quality productive force can provide technical support for enterprises' green technological innovation. The mechanism of action is reflected in three aspects: Firstly, the integration of advanced materials application and intelligent technologies drives the improvement of resource element utilization efficiency and accelerates the formation of green competitive advantages; Secondly, through technologies such as digital twins, shorten the development cycle of clean technologies and enhance the market responsiveness of environmentally friendly products; Finally, build a closed-loop system of "R&D - production - recycling" to realize the ecological reconfiguration of the innovation value chain.

New quality productive force empowers enterprises' green technology innovation through the upgrading of human capital structure. High-tech talents can bring advanced expertise and technology to the R&D, production and operation of the enterprise, and the increase in the proportion of high-tech talents in the enterprise can further innovate through the aggregation and sharing of resources such as technology to enhance the overall resource control ability of the enterprise, thereby achieving the upgrading of the enterprise's green technology. As a result, the following assumption is proposed:

Hypothesis 2: New quality productive force promotes the improvement of green technology innovation capabilities of enterprises.

2.3 The Impact of Digital Transformation on New Quality Productive Force

Digital transformation, with the use of data elements as the means, the application of digital technologies as the core, the development of digital business as the focus, and the integration into the digital ecosystem as the path [12], provides dual support for the evolution of new quality productive force-intelligent technology foundation and human capital upgrade. As a result, the following assumption is proposed:
Hypothesis 3: Digital transformation has a positive impact on new quality productive force.

2.4 The Mediating Role of New Quality Productive Force

The new quality productive force consists of three core dimensions: the new type of labourer, the new type of subject of labour, and the new type of means of labour, and a symbiotic mechanism of elements is formed among these dimensions through a digital collaborative network [13]. The digital transformation of enterprises has a positive effect on improving the level of green technology innovation of enterprises by generating new types of workers, new types of means of labor and new types of objects of labor.
Firstly, the digital transformation of enterprises is driven by digital technology, and the application of digital technology relies on highly skilled and high-quality talents, which forces human capital to transform towards "digital" capabilities and gives rise to new types of labourers, and these new types of labourers often, due to their dual capabilities in digital technology and ecological design, can promote the improvement of enterprises' green technology capabilities; Secondly, the digital transformation of enterprises can upgrade the means of labour through big data, and this higher technological content of the means of labor can promote efficiency improvement, thereby promoting green technology innovation of enterprises; Finally, digital transformation of enterprises can generate demand for new energy and new materials and give rise to new types of labor objects, which can quickly integrate different resources, facilitate more convenient and rapid information collection in various industries, accelerate technology exchange and cooperation, and provide a material basis for promoting green technology innovation. Therefore, the following assumption is proposed:
Hypothesis 4: New quality productive force plays a mediating role in the relationship between digital transformation and green technological innovation. That is, digital transformation can influence green technology innovation in manufacturing enterprises through the path of new quality productive force.

3 Theoretical Analysis and Research Hypotheses

3.1 Sample Selection and Data Collection

This study takes the data of A-share listed companies on the Shanghai and Shenzhen stock exchanges from 2012 to 2023 as the research sample. To ensure the validity of the study, A three-stage data sorting process was carried out: Firstly, the data values of financial enterprises are excluded; Secondly, special treatment and delisting warning companies (ST/PT labels) are excluded; Finally, abnormal samples with a financial indicator missing rate of more than 30% and negative net assets are excluded. In addition, to avoid the interference of extreme values, this paper truncates the continuous variables by 1% above and below. The basic financial data is derived from the cross-validation of the CSMAR Economic and Financial Research database and the Wind Information Financial terminal. The innovation indicators are obtained through the CNRDS Innovation Research database, and the unstructured text information is collected from the official information disclosure platforms of the Shanghai Stock Exchange and the Shenzhen Stock Exchange.

3.2 Variable Measurement

3.2.1 Digital transformation (DT)

This paper draws on the practice of Wu Fei et al.[14], extracting key words related to digital transformation from corporate annual reports and constructing proxy variables for digital transformation through word frequency statistics. Due to the extremely right-skewed nature of the word frequency statistics, the summed word frequencies were summed and logarithmised.

3.2.2 New quality productive force (Nqd)

This paper draws on the practice of Song Jia et al. [15] and uses the entropy method to calculate the weights of each indicator to construct an indicator system of enterprise new quality productive force, as shown in Table 1.

3.2.3 Green technology innovation (Green)

Referring to the practice of Wang Xin et al.[16], green invention and green utility model patents are selected to measure the level of green technology innovation. The specific approach is to first sum up the quantities and add one, and then take the natural logarithm.
In addition, referring to existing studies[14], the age of the enterprise, the size of the enterprise, the debt-to-asset ratio, etc. are selected as control variables.

Table 1 New Quality Productive Force Index System of Enterprises

Factors	Sub-factor	Indicators	Indicator explanation
Labourer	Live labor	Research and development personnel salary proportion	(R&D expenses - salary and compensation)/Revenue
		Proportion of R&D personnel	R&D personnel/Total staff
Subject of labour	Materialized labor	Proportion of highly educated personnel	Number of people with a bachelor's degree or above/Number of employees
		Proportion of fixed assets	(R&D expenses - Payroll)/Operating income
		Proportion of manufacturing expenses	(Cash outflow from operating activities + Depreciation of fixed assets + Amortization of intangible assets + Provision for impairment - Cash paid for purchasing goods and services - cash paid to employees and on behalf of employees)/Cash outflow from operating activities + Depreciation of fixed assets + Amortization of intangible assets + Impairment allowance)
Means of labour	Hard tech	R&D depreciation and amortization ratio	(R&D expenses - depreciation and amortization)/Operating income
		R&D lease expenses ratio	(R&D expense - Lease fee)/Operating income
		Proportion of direct investment in R&D	(R&D expense - Direct input)/Operating income
		Proportion of intangible assets	Intangible assets/Total assets
	Soft tech	Total asset turnover rate	Operating income/Average total assets
		Reciprocal of equity multiplier	Owner's equity/Total assets

3.2 Regression Model

In this paper, a multiple hierarchical regression model is established to empirically test the relationship between digital transformation, new quality productive force and green technology innovation in the following steps:
The first step is to take the control variable as the independent variable and analyze its relationship with green technology innovation, and construct the model as follows:

$$Green_{it} = \alpha_0 + \sum \alpha_1 control_{it} + \varepsilon_{it} \quad (1)$$

where $Green_{it}$ is green technology innovation; $controls_{it}$ is the control variable; i is enterprise; t is year; ε_{it} is error.
Step 2: Examine the relationship between digital transformation and green technology innovation. Introducing digital transformation on the basis of Equation (1), the model is constructed as follows:

$$Green_{it} = \alpha_0 + \alpha_1 DT_{it} + \sum \alpha_2 control_{it} + \varepsilon_{it} \quad (2)$$

Step 3: Examine the relationship between digital transformation and new quality productive force. With new quality productive force as the dependent variable, the model is constructed as follows:

$$DT_{it} = \alpha_0 + \alpha_1 Nqd_{it} + \sum \alpha_2 control_{it} + \varepsilon_{it} \quad (3)$$

Step 4: Examine the relationship between new quality productive force and green technology innovation. Introducing new quality productive force on the basis of equation (1), the model is constructed as:

$$Green_{it} = \alpha_0 + \alpha_1 Nqd_{it} + \sum \alpha_2 control_{it} + \varepsilon_{it} \quad (4)$$

Step 5: To verify the mediating role of new quality productive force in the relationship between digital transformation and green technology innovation, new quality productive force is introduced based on equation (4), and the mediating role of new quality productive force is judged by combining model (3) and model (4). the model is constructed as follows:

$$Green_{it} = \alpha_0 + \alpha_1 DT_{it} + \alpha_2 Nqd_{it} + \sum \alpha_2 control_{it} + \varepsilon_{it} \quad (5)$$

4 DATA PROCESSING AND RESULT ANALYSIS

4.1 Descriptive Statistics

Table 2 shows the descriptive statistics of the variables. The standard deviation of digital transformation is less than that of green technology innovation, indicating that the DT score of A-share listed companies is more concentrated than that of green. The standard deviation of the mediating variable Nqd is greater than that of other variables, indicating that the new quality productive force level of A-share listed companies varies greatly.

Table 2 Descriptive Statistics of The Variables

Variables	Observations	Mean value	Standard deviation	Maximum	Minimum
Green	34579	0.367	0.782	6.518	0.000

DT	34579	1.431	1.397	5.063	0.000
Nqd	34579	5.093	2.503	14.464	0.685
Firm_age	34579	2.980	0.324	3.562	1.967
Size	34579	22.44	1.294	26.890	19.657
Lev	34579	0.424	0.205	0.902	0.065
Cashflow	34579	0.047	0.069	0.246	-0.167
ROA	34579	0.039	0.065	0.256	-0.272
Bm	34579	1.060	1.174	7.224	0.093

4.2 Correlation Analysis

The results of the correlations among the variables are shown in Table 3. The correlation coefficient between DT and Green is significantly positive, preliminarily confirming that digital transformation has a positive transmission effect on green technology innovation, and H1 holds. Similarly, Hypothesis 2 and 3 are preliminarily verified. In addition, an analysis of the average VIF value and the maximum VIF value of each variable reveals that both are less than 10, thus confirming the absence of multicollinearity.

Table 3 Correlation of Variables

Variable	Green	DT	Nqd	Firm_age	Size	Lev	Cashflow	ROA
Green	1							
DT	0.241***	1						
Nqd	0.179***	0.222	1					
Firm_age	0.071	0.222***	0.345	1				
Size	0.303***	0.229***	0.342	0.168	1			
Lev	0.013	0.297***	0.281***	0.286	0.464***	1		
Cashflow	0.038***	0.054	0.026	0.056	0.161	0.074	1	
ROA	0.176	0.186	0.076***	0.286**	0.057	0.176***	0.034	1
Bm	0.016	0.265***	0.086	0.246	0.081***	0.038	0.236***	0.347

Note: *, **, ***represent significant correlation at the 10%, 5%, and 1% levels, respectively. The same below.

4.3 Analysis of Regression Results

4.3.1 Direct effects analysis

Based on the analysis of correlations, this paper extends the testing of hypotheses through the implementation of multivariate hierarchical regression. Model 1 in Table 4 incorporates solely control variables, while Model 2 incorporates DT variables based on Model 1. It is evident that the digital transformation of enterprises can enhance their green technology innovation capacity, thereby validating hypothesis 1.

The dependent variable of Model 3 is New quality productive force, with control and digital transformation variables included in the model. The findings of the test demonstrate a significant positive relationship between digital transformation and New quality productive force. Consequently, hypothesis 2 is substantiated. In this study, Model 4 is employed to analyse the relationship between the mediator variable Nqd and green technology innovation. The findings indicate that Nqd can contribute to the upgrading of green technology levels, thereby validating hypothesis 3.

4.3.2 Mediating effect analysis

As demonstrated in the preceding analysis, both digital transformation and new quality productive force exert a substantial positive influence on green technological innovation. Model 4 in Table 4 incorporates the DT variable as model 5. Upon observing models 5 and 2 and 4, it becomes evident that the regression coefficients of DT and Nqd are diminished to a certain extent, yet remain significant at the 1 per cent level.

To further verify the mediating effect of new quality productive force, on this basis, BOOTSTRAP was used to verify the indirect effect of new quality productive force between digital transformation and green technology innovation. The mediating effect of new quality productive force was 0.275, and the confidence intervals were [0.189, 0.251], excluding 0. Therefore, Hypothesis 4 was validated.

Table 4 Regression Models and Significance Tests

Variables		Dependent variable				
		Green	Green	Nqd	Green	Green
		Model 1	Model 2	Model 3	Model 4	Model 5
Control variables	Firm_age	-0.161***	-0.129***	0.498	0.318**	0.289**
	Size	0.291**	0.232	0.194**	0.067	0.054
	Lev	-0.218	-0.162**	-0.089	0.163**	0.148**
	Cashflow	2.619	2.289**	2.019**	3.716	3.683
	ROA	-2.692	-2.281	0.891*	2.761***	2.543**
	Bm	-0.152	-0.117*	-0.177	0.051**	0.039
Independent variables	DT	—	0.329***	0.428***	—	0.297***
Mediating variables	Nqd	—	—	—	0.519***	0.425***
R^2		0.287	0.487	0.672	0.631	0.628

F value	5.892***	26.413***	31.789***	37.719***	35.816***
Adjusted R^2	0.217	0.429	0.618	0.592	0.572

4.4 Robustness Analysis

To test the reliability of the above regression results, referring to the practice of Yuan Weihai et al.[17], the total factor productivity of enterprises is used to measure the level of new quality productive force of enterprises, and the results of empirical analyses in this paper remain robust according to the models 1-4 shown in Table 5. Referring to the practice of Yuan Chun et al.[18], digital transformation is measured by the sum of the frequency of digitally related words of enterprises divided by the length of MD&A segments of annual reports, and the results are still robust (the regression coefficients of the variables of Models 1-3 are 0.167, 0.253, and 0.293 in that order, and in Model 4, the results of the DT regression are 0.213, and the results of the Nqd regression are 0.237, and they are significant at the level of 1 per cent). Referring to the practice of Ren et al.[19], the ratio of green patents granted by listed companies to all patents granted in that year is re-measured as green technological innovation, and the results are still robust. (The regression coefficients of the variables in Models 1-3 are 0.253, 0.286, and 0.381 in that order, and the DT regression result in Model 4 is 0.229, and the Nqd regression result is 0.262, and it is significant at the 1% level).

Considering the possible differences in aspects such as government policy support among regions[17], the relevant data of enterprises in municipalities directly under the Central Government were excluded and the test was conducted again. The test results are shown in Model 5-8 of Table 5. The research hypothesis of this paper still holds.

Table 5 Robust Analysis

Variables		Dependent variable							
		Green	Nqd	Green	Green	Green	Green	Nqd	Green
		Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
Control variables	Firm_age	-0.189	0.378	0.809**	0.249**	-0.161	0.430	0.374**	0.245**
	Size	0.368	0.196**	0.047	0.024	0.292	0.158**	0.377	0.034
	Lev	0.046**	-0.160	0.259**	0.163**	-0.498**	-0.029	0.266**	0.136**
	Cashflow	1.783**	2.416**	3.736	3.896	3.892**	3.514**	3.378	3.253
	ROA	-1.820	0.067*	2.891**	2.589**	-2.631	0.638*	2.268	2.243**
	Bm	0.062*	-0.165	0.189**	0.076	-0.186*	0.873	-0.035**	0.062
Independent variables	DT	0.271***	0.378***	—	0.243***	0.386***	0.416***	—	0.326***
Mediating variables	Nqd	—	—	0.568***	0.496***	—	—	0.635***	0.523***
R^2		0.381	0.654	0.684	0.628	0.647	0.682	0.635	0.754
F value		18.89**	39.749**	47.989**	38.530**	42.749**	57.39**	45.34**	45.893**
Adjusted R^2		0.317	0.598	0.628	0.592	0.613	0.637	0.592	0.683

5 RESEARCH CONCLUSIONS AND DEFICIENCIES

This study utilises the dynamic panel data of A-share listed companies in Shanghai and Shenzhen from 2012 to 2023 in order to empirically examine the relationship between digital transformation, new quality productive force and green technology innovation. The findings of this study demonstrate that the acceleration of digital transformation and the augmentation of new quality productive force can substantially enhance green technological innovation. The outcomes of the mediation mechanism test reveal that digital transformation can indirectly promote the enhancement of green technological innovation capacity through the promotion of new quality productive force, and this conclusion remains consistent after conducting multiple robustness tests.

Although this paper examines the impact of digital transformation on green technology innovation from the perspective of new quality productive force, there are still many deficiencies Firstly, with regard to the measurement of variables, although the study draws on previous research, there is still the possibility that the quantification is not sufficiently precise. For example, the specific measurement of the three aspects of new quality productive force is inevitably missing in a small aspect due to a paucity of previous research. Secondly, due to the limitation of space, the empirical part of this paper does not analyse the specific mechanism of new quality productive force on green technology innovation in more detail.

In response to these deficiencies, the future research direction is as follows: Firstly, with the continuous enhancement of future data mining technology and the deepening of research on new quality productive force, subsequent research on new quality productive force and digital transformation can be quantified using a multi-dimensional evaluation system instead of being confined to a single evaluation indicator. Secondly, future research on the impact mechanism of digital transformation on green technology innovation can be further explored. For example, explore the role of digital technology and dynamic capabilities in the process of the impact of digital transformation on green technology innovation.

COMPETING INTERESTS

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