Can Digital Transformation in Enterprises Improve Green Total Factor Productivity? An Empirical Study Based on Data from Chinese Listed Companies

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Abstract. The article is based on data from China's A-share listed companies from 2007 to 2022, empirically examining ow corporate digital transformation influences overall green productivity. The study indicates that the implementation of corporate digital transformation has a substantial positive impact on green total factor productivity (GTFP). This finding remains consistent even after undergoing rigorous robustness tests. Heterogeneity test results indicate that regions in the central and west the central, heavily polluting industries, and large-scale enterprise samples, the improvement effect of digital transformation among corporation on supply chain efficiency is more pronounced. Mechanism analysis suggests that digital transformation positively influences GTFP by promoting green innovation and enhancing supply chain efficiency. The research findings contribute to uncovering the inherent logic behind advancing the GTFP of companies through digital transformation, providing inspiration and reference for advancing high-quality development in businesses.

Keywords: Digital transformation, Green total factor productivity, Green innovation, Supply chain efficiency, High-quality development.

1. Introduction

As China's digital economy enters a rapid development stage, digitalization gradually becomes the most promising and dynamic economic model, playing a crucial role in improving factor allocation efficiency and resource utilization. The deepening integration of digital technologies like blockchain with the tangible economy persists. Companies consider digital transformation as an effective means to enhance competitiveness, achieve transformation and upgrading, and improve production efficiency. They rapidly advance digitalization, utilizing these technologies to optimize production, operations, and management, aiming to boost green total factor productivity (GTFP) and attain high-quality development.

On the other hand, China's economy is rapidly transitioning to a green and high-quality development path. China has put forward the significant strategic goal of "peaking carbon emissions by 2030 and achieving carbon neutrality by 2060," with the aim of building a community of shared future for humanity and nature to achieve sustainable development. Attaining the objective of decreasing carbon emissions is seen as a crucial path towards realizing objectives related to carbon peaking and carbon neutrality.

Enhancing GTFP will encourage businesses to adopt clean technologies, implement circular economy practices, and introduce energy-saving measures, thereby minimizing waste and emissions and ensuring the sustainable utilization of resources. Moreover, fostering the enhancement of GTFP can alleviate environmental burdens, achieving synergy between environmental protection and economic development. This involves encouraging businesses to focus on reducing carbon emissions and promoting energy efficiency in their production activities to address climate change and propel advancing towards a carbon-neutral economy.

In light of the aforementioned context, scholars, both domestically and internationally, have been keenly focused on exploring to connect digital transformation with the comprehensive productivity associated with green practices. Existing literature primarily investigates the link between digitalization and overall productivity in environmentally sustainable practices, considering macro,

meso, and regional perspectives. At the macro level, digital transformation, through the application of advanced technologies and data analysis methods, has been shown to enhance the effectiveness of production processes and the use of resources (Zhang et al., 2022) [1], significantly improving GTFP and reducing environmental impact and energy consumption (Liu et al., 2022) [2]. Additionally, digital transformation promotes information sharing and communication, enhances decision-making capabilities for businesses and governments, and drives the development of green technology and innovation, thereby facilitating high-quality green urban development [3]. However, Zhang et al. (2022) [4] proposed a positive "U" relationship linking the extent of digitalization with the total factor productivity related to green initiatives in urban areas. Meaning that the favorable influence on the total factor productivity of green initiatives in urban areas. Occurs only after the digital development level surpasses a certain threshold. Conversely, Da et al. (2023) [5] argued that the economy shaped by digital advancements, through the mechanisms of industrial structure dividends and human capital structure dividends, has heterogeneous effects on urban GTFP.

At the meso level, existing literature predominantly focuses on the incorporation of digital solutions in specific industry sectors, resulting in an enhancement of GTFP. Deng H et al. (2022) [6] discovered that the techno-economic paradigm has a substantial enhancement on GTFP within the manufacturing sector, while Hao X et al. (2023) [7] proposed that the technologically influenced economy significantly enhances the growth of GTFP in the manufacturing sector, with spillover effects of digital economic levels in surrounding areas effect green productivity growth positively. These research findings indicate that digital transformation at the meso level, there is a beneficial influence on GTFP.

At the regional level, taking China as an example, the impact of techno-economic paradigm on the development of green total factor varies across regions. The influence of digitization on GTFP is greater in the west and middle locales compared to the western region (Zhao J et al., 2022) [8]. Non-core cities exert a greater marginal effect than core cities (Liu et al., 2022) [9]. Thus, the ramification of digital transformation on regional GTFP is shaped by characteristics and developmental levels unique to each region.

In summary, researchers have explored the link between digital transformation and the comprehensive productivity associated with environmentally friendly practices, considering a range of perspectives. However, there are still limitations in the existing research. Micro-level enterprises, as integral components of the macroeconomy, profoundly impact the overall economic situation through their total factor productivity. In the realm of quality development with a green perspective, improving the GTFP of businesses is a critical issue. However, the majority of research has concentrated on how digital transformation affects GTFP at the macroeconomic level or within specific industries. There remains a shortage of empirical studies examining the relationship between digital transformation and GTFP in micro-level across diverse industries.

Distinguishing Features of This Study from Prior Research: (1) Taking a micro-level perspective, the paper analyzes and empirically examines the impact mechanism of corporate digital transformation on micro-level GTFP, contributing to the enrichment of theoretical research content. (2) Introducing green innovation and supply chain efficiency as mediating variables, the study explores the indirect mechanisms through which digital transformation enhances GTFP, broadening our comprehension of how digital transformation enhances GTFP. (3) Further investigation into factors such as scale and nature contributes to a more in-depth exploration of the constraints on the differential impact of digital transformation on GTFP, enhancing the study content focuses on the factors influencing the connection between digital transformation and GTFP.

This study contemplates investigating the influence of corporate digital transformation on GTFP and exploring the influence on such productivity. Therefore, investigating the significance of digital transformation's influence on the crucial advancement of China's green economy relies on the GTFP of companies and the achievement of sustainable environmental practices in the business sector. Simultaneously, a thorough exploration of the influence and mechanisms through which digital transformation affects the GTFP of enterprises is of crucial significance. It provides valuable insights

for businesses aiming to achieve a harmony between economic advantages and environmental considerations, contributing to the meaningful reference for the green development of enterprises.

Building upon this rationale, the study employs the research sample comprises Chinese A-share listed companies spanning from 2007 to 2022. Initially, it performs theoretical analysis and empirical tests to explore the influence of corporate digitalization on GTFP. Subsequent robustness tests are conducted to verify precision and reliability of the research findings. Secondly, the research investigates the diversity within corporate digital transformation from three perspectives: regional location, industry characteristics, and company scale. Finally, it delves into the impact mechanisms of corporate digital transformation from the aspects of green innovation and supply chain capabilities.

The subsequent sections are organized as follows: the second section covers theoretical analysis and research hypotheses, followed by the third section detailing research design; the fourth part involves empirical analysis, while the fifth part focuses on mechanism analysis; the concluding sections include the conclusion and policy recommendations.

2. Theoretical Analysis and Hypothesis

2.1. The direct impact of enterprise digital transformation and GTFP

Enterprise digital transformation means the utilization of information technology and digital means to transform and upgrade traditional business operations, adapting to the demands and challenges of the digital era. GTFP refers to the efficiency and effectiveness with which a company comprehensively utilizes resources, energy, and the environment in its production process. Digital transformation directly impacts GTFP by increasing production efficiency, optimizing resource utilization, and reducing environmental impact, achieving a situation where both the economy and the environment benefit concurrently.

In terms of resource utilization, enterprise digital transformation can achieve optimal resource utilization through optimized resource allocation and refined management. Through techniques such as data analysis and simulation, companies can better predict and plan production needs, strategically allocate and manage resources, and implement refined management practices to reduce resource waste and loss, ultimately enhancing resource utilization efficiency.

Regarding environmental impact, enterprise digital transformation can mitigate negative environmental effects through green innovation and environmental management practices (Sun et al., 2022) [10]. Digital transformation enables companies to monitor and control environmental indicators more effectively. By introducing intelligent monitoring systems and embracing sustainable development principles, companies can monitor and analyze environmental data in real-time, promptly identify and address environmental issues. Furthermore, digital transformation facilitates the greening of production processes and the implementation of a circular economy, thereby reducing negative environmental impacts, increasing resource recycling rates, and achieving sustainability goals.

In conclusion, enterprise digital transformation has a direct impact on GTFP. Based on this, we propose the hypothesis:

H1: Enterprise digital transformation can promote the improvement of GTFP.

2.2. The indirect impact of enterprise digital transformation and GTFP

Based on the essence and role of corporate digitalization, it can be observed that through the enhancement of green innovation and supply chain capability, the digital transformation of businesses has the potential to enhance GTFP. Under the impetus of digital transformation, companies can optimize the combination of labor, capital, data, energy, and other production factors, stimulate innovation potential, enhance overall labor quality, and create a dual-driving engine of technological innovation and labor factors, unleashing the dividends of the digital economy. This transformation has created a new scenario of synergistic development between digitization and greenization for

manufacturing enterprises, maximizing positive economic output, while simultaneously reducing negative environmental output, contributing to sustainable development.

The research investigates the indirect pathways through which digital transformation in manufacturing enterprises affects their GTFP. The exploration is conducted from the perspectives of the environment, economy, and society.

2.2.1. The mediating role of green innovation

Green innovation is one of the crucial mechanisms in the digital transformation of enterprises. The digital transformation of enterprises can influence GTFP through green innovation (Li & Fang, 2023) [11], bringing about a series of positive changes at the environmental, economic, and social levels.

Firstly, at the environmental level, green innovation can assist enterprises in reducing resource consumption and energy emissions. Digital transformation can achieve fine-grained management and optimization of the production process through the application of information technology, thereby reducing energy waste and environmental pollution. For instance, through technologies companies can monitor and control the energy consumption of production equipment in real-time, precisely managing energy usage to achieve energy conservation and emission reduction goals. Furthermore, digital transformation can drive companies to shift from traditional linear economic models to circular economic models, reducing resource consumption and environmental pressure through methods like product remanufacturing and waste recycling.

Secondly, at the social level, green innovation has the potential to foster sustainable development and social responsibility of enterprises. Digital transformation can facilitate information sharing and collaboration in green value chains among enterprises, supply chain partners, customers, and consumers (Blut M et al., 2021) [12], propelling the entire industry towards sustainable development. Through the practice of green innovation, enterprises can establish a positive corporate image and brand image, enhancing consumer recognition and loyalty.

In summary, the digitization of enterprises has a notable influence on GTFP through the avenue of green innovation. Therefore, we posit the hypothesis:

H2: The implementation of digital transformation in businesses has the potential to improve the overall green productivity of manufacturing companies through the empowerment of green technological innovation.

2.2.2. The Mediating Role of Supply Chain Capability

Supply chain capability is a core competency for enterprises in supply chain management, encompassing supplier selection and management as well as logistics operations. By enhancing supply chain capability, enterprises can positively impact GTFP, achieving sustainable development goals at the environmental and economic levels.

Firstly, at the environmental level, enhancing supply chain capacity can assist enterprises in achieving green logistics and reducing environmental pollution. Through digital transformation, companies can incorporate technologies to achieve the visualization and intelligent management of the supply chain. This can enhance the efficiency of logistics operations, reduce transportation distances and times, and decrease energy consumption and emissions (Zhang et al., 2023) [13]. Furthermore, digital transformation can optimize inventory management, reduce surplus inventory and waste generation, thereby minimizing adverse environmental impacts.

Secondly, at the economic level, the enhancement of supply chain capability can realize green cost control and create economic value. Through digital transformation, companies can achieve the digitization of the supply chain and promote information sharing, enhancing the responsiveness and flexibility of the supply chain. This aids in lowering procurement, production, and logistics costs, improving the competitiveness and profitability of the enterprise. Furthermore, through the improvement of supply chain capability, digital transformation can facilitate innovation between companies and supply chain partners (Chen & Wu, 2022) [14]. Through the utilization of digital technology, companies can engage in real-time sharing of data and collaborative decision-making across various supply chain components. This facilitates accurate matching of supply and demand,

encourages the shared use of resources, and supports the advancement of green supply chain management and innovation.

In conclusion, the digital transformation of enterprises can positively impact GTFP through the enhancement of supply chain capability. Therefore, we posit the hypothesis:

H3: The digitization of businesses has the potential to boost overall green productivity of manufacturing companies through the empowerment of supply chain capability.

3. Research Design

3.1. Sample Selection and Data Source

This research utilizes A-share listed companies on the Shanghai and Shenzhen stock exchanges spanning from 2007 to 2021 as the sample for investigation. All ST, *ST, delisted during the period, and financial industry companies are excluded from the sample. To control for estimation errors caused by outliers, a two-tailed trimming of 1% for all continuous variables at the micro-enterprise level is applied. Sample data is sourced from the CSMAR database.

3.2. Variable Definitions

3.2.1. Dependent Variable

Green total factor productivity (GTFP) of enterprises. Regarding the measurement of enterprise total factor productivity, methods include parametric and non-parametric approaches. This study incorporates environmental pollution into the evaluation system and, drawing on the approach of Cui & Lin (2019) [15], employs the non-radial SBM-ML index (hereafter referred to as "ML index") to measure enterprise GTFP. The measurement of input and output indicators for enterprise GTFP is as follows. (1) Input factors: The workforce is indicated by the count of employees within the enterprise; financial capital input is reflected by the net value of fixed assets in the enterprise; energy input is computed using the industrial electricity consumption in the city where the enterprise is situated, adjusted by the proportion of employees in the city to the urban employment of the total population. (2) Expected output: This study uses the enterprise's operating income as a proxy variable for expected output. (3) Non-expected output: This research computes the "industrial three wastes," specifically industrial sulfur dioxide, industrial wastewater, and industrial dust emissions, based on the proportion of employees in the city to the urban employment of the total population, as a proxy variable for non-expected output. Since the calculated ML index indicates the pace of change in enterprise GTFP, following the approach of Huang et al. (2021) [16], the GTFP metric for A-share listed companies in China spanning from 2007 to 2021 is obtained.

3.2.2. Independent Variable

Degree of enterprise digital transformation (Digit). Following the approach of Zhao (2021) [17], a web crawler software is used to tabulate the occurrence of 99 terms related to digital aspects in the annual reports from the CSMAR database across four dimensions: the utilization of digital technology, internet business models, intelligent manufacturing, and modern information systems. These frequencies are categorized and summarized, with the total frequency of terms in these four aspects serving as the representation of the extent of digital transformation within the enterprise. The natural logarithm is applied after adding 1 to this representation.

3.2.3. Mediating Variables

Total green innovation (EnvrPat). This study measures the quantity of green innovation by the number of green patents applied for by listed companies. The construction of this indicator follows the method of patent indicators in Qi et al. (2018) [18]. The count of green utility patents (EnvrUtyPat) and green invention patents (EnvrInvPat) submitted by listed companies in the present year is logged and summed to represent the quantity of green innovation.

Supply chain efficiency (Stock_day). Considering that the inventory turnover days of enterprises effectively overcome measurement errors caused by the retention of safety stock and reflect the dialogue frequency and trade exchanges between upstream and downstream enterprises in the supply chain, it is an indicator of supply chain flexibility and response speed, which corresponds to the current reality of overcapacity. Following the approach of Zhang et al. (2023) [13], this study uses the inventory turnover days to reflect supply chain efficiency, calculated as ln (365/inventory turnover ratio) based on the inventory stock of enterprises. A lower turnover days value indicates faster inventory realization, higher efficiency in logistics, information flow, and capital flow within the supply chain nodes.

3.2.4. Control Variables

To avoid interference from other factors in the research conclusions, and following existing studies, control variables such as company size (Size), debt-to-equity ratio (Lev), return on assets (ROA), operating cash flow (Ocf), sales growth rate (Growth), company age (Age), Tobin's Q (Tobinq), management expense ratio (Mfee), concentration of equity (TOP1), proportion of independent directors (Dpe), and board size (Board) are selected. Detailed explanations and descriptive statistical analyses of these variables are provided in Table 1.

Table 1. Descriptive statistics of variables.

Variable	Variable definitions	N	Mean	Sd	Min	Max
GTFP	Green total factor productivity of enterprises	37,525	0.9911	0.1199	0.7200	1.1760
Digit	ln (total number of words for enterprise digital transformation + 1)	37,525	2.8196	1.2713	0	5.8377
Stock_Day	ln (365/Inventory Turnover)	37,201	4.4487	1.2662	-0.2032	7.6960
EnvrPat	ln (The total number of green patent applications +1)	37,525	0.3214	0.7524	0	6.8480
Size	Logarithm of total assets	37,525	22.1876	1.3067	19.6534	26.2376
Lev	Ratio of total liabilities to total assets	37,525	0.4396	0.2086	0.0573	0.9501
Roa	Ratio of net profit to total assets	37,525	0.0347	0.0664	-0.2792	0.2059
Ocf	Ratio of net cash flow to total assets	37,525	0.1574	0.1204	0.0091	0.5964
Growth	Main business income ratio, growth rate of main business income compared to the previous year	37,525	0.3545	0.9805	-0.7031	6.9506
Age	ln (Listing Age +1)	37,525	2.3428	0.6569	1.0986	3.4011
Tobinq	Ratio of market value of the company to reset capital	37,525	2.0859	1.38506	0.8473	9.0297
Mfee	Ratio of management expenses to total assets	37,525	0.0878	0.0736	0.0081	0.4643
Top1	Shareholding percentage of the largest shareholder	37,525	0.3422	0.1487	0.0843	0.7398
Dpe	Ratio of independent directors to board size	37,525	0.3749	0.0534	0.3077	0.5714
Board	ln (number of directors +1)	37,525	2.2462	0.1778	1.7917	2.7725

3.3. Model Specification

Investigating the influence of corporate digital transformation on GTFP, the following econometric model is specified:

$$GTFP = \beta_0 + \beta_1 Digit_{it} + \gamma CV_{it} + \alpha_i + \alpha_t + \varepsilon_{it} \quad (1)$$

Where the dependent variable is green total factor productivity (*GTFP)* the core independent variable is enterprise digital transformation (*Digit*), CV_{it} signifies a set of control variables, $\alpha_i$stands for the fixed effect of the enterprise, $\alpha_t$is a time-fixed effect that controls a series of exogenous shocks that change over time but not with cities. ε_{it}Is the error term, and enterprise fixed effects are controlled for.

4. Empirical results

4.1. Analysis on benchmark regression results

To explore the influence of enterprise digital transformation on GTFP, this study initially analyzes the direct consequences of digital transformation on GTFP. Table 2 presents the fundamental regression findings. Column (1) considers only the core independent variable while adding enterprise fixed effects. The results show that the promotion effect of enterprise digital transformation on GTFP is significant at the 1% level. In column (2), a series of control variables are introduced, and the coefficient of the core independent variable remains significantly positive at the 1% level. This indicates that digital transformation significantly enhances overall factor productivity. Thus, hypothesis 1 is validated.

Additionally, the coefficients of control variables Lev and Roa are -0.0958 and -0.0525, respectively, both negatively significant at the 1% level. This suggests that a high debt-to-equity ratio may lead to significant financial pressure on companies, making them more inclined to adopt short-term, economically beneficial practices rather than making long-term environmental investments, thus affecting GTFP. Adopting green production methods may require additional investment and costs, negatively impacting the return on assets. To improve asset returns, companies may limit expenditures on environmental protection, resulting in a negative correlation between Roa and GTFP. The coefficients of Size and Ocf are 0.0279 and 0.0726, respectively, positively significant at the 1% level. This indicates that larger companies with stronger fundraising and profitability capabilities increase their investment in environmental benefits, thereby promoting the improvement of GTFP. Sufficient cash flow can be used for research and development and the adoption of more environmentally friendly technologies, enabling companies to enhance production efficiency, reduce energy and raw material consumption, and ultimately improve GTFP.

Table 2. Benchmark regression results.

	(1) *GTFP*	(2) *GTFP*
Digit	0.0864*** (88.3881)	0.0164*** (21.1425)
Size		0.0279*** (20.1070)
Lev		-0.0958*** (-17.6605)
Roa		-0.0525*** (-7.2419)
Ocf		0.0726*** (12.4116)
Growth		-0.0007* (-1.7039)
Age		0.2159*** (88.9137)
Tobinq		-0.0019*** (-4.0784)
Mfee		0.0361*** (3.3569)

Top1		0.0410***
		(4.4955)
Dpe		0.0294*
		(1.7698)
Board		-0.0341***
		(-5.1770)
_cons	0.7476***	-0.0958***
	(271.3694)	(-2.8953)
Enterprise *FE*	Yes	Yes
Year *FE*	Yes	Yes
N	37525	37525
R^2	0.3874	0.8268
Adj. R^2	0.3873	0.8268

Notes: *, ** and *** represent the significance levels of 10%, 5% and 1%, respectively; the corresponding T-values are in parentheses.

4.2. Robustness Analysis

4.2.1. Replacement of Core Explanatory Variables

In column (1), the primary explanatory variables were substituted with an indicator pertaining to the level of digital transformation in publicly traded companies proposed by Wu et al. (2021) [19], calculated through a keyword frequency text analysis method. Specifically, the method involved using web crawling software to perform word frequency statistics on key terms related to "ABCD" (artificial intelligence, blockchain, cloud computing, big data) technology and digital technology in the annual reports of companies in the CSMAR database. The frequencies were categorized and summarized, with the total frequency of these five aspects serving as an indicator of the degree of digital transformation for companies. The natural logarithm of the sum, incremented by 1, was then taken. The estimation results are presented in Table 3, column (1), where it can be observed that after replacing the core explanatory variables, the estimated coefficients for the Digit variable are consistently significant at the 1% level.

4.2.2. Exclusion of Outlier Sample Data

To mitigate the potential impact of the COVID-19 pandemic on the research results, this study excluded data from the years 2019 to 2021 and re-conducted the regression analysis. The results in Table 3, column (2), indicate that even after excluding the three years significantly affected by the pandemic, the coefficient for Digit remains significantly positive, further reinforcing the research findings.

Table 3. Robustness analysis results.

	(1) *GTFP*	(2) *GTFP*
Digit	0.0124***	0.0173***
	(17.8421)	(21.4200)
_cons	-0.1112***	-0.1401***
	(-3.3431)	(-4.0782)
Control variable	Yes	Yes
Enterprise *FE*	Yes	Yes
Year *FE*	Yes	Yes
N	37525	29777
R^2	0.8244	0.8387
Adj. R^2	0.8244	0.8386

Note: *, ** and *** represent the significance levels of 10%, 5% and 1%, respectively; The corresponding T-values are in parentheses.

4.3. Heterogeneity Analysis

4.3.1. Regional Heterogeneity

To further analyze the spatial distribution of companies, we categorized the 31 provinces in China into three regions: East, Middle, and West—based on the economic geography concepts published by the National Bureau of Statistics. Taking into account regional resource endowments and technological differences, the Eastern region generally exhibits higher levels of marketization and resource allocation efficiency. In the East, conventional factors such as capital and labor make a more significant contribution to economic growth. Consequently, the economy shaped by digital advancements has a relatively smaller ramification on the high-quality development of Eastern region companies. In contrast, the marketization level in the Middle and Western regions is significantly lower, with lower information transmission efficiency. The Central region ranks second, while the Western region lags behind. The advancement of the tech-driven economic landscape is advantageous for establishing information communication bridges, alleviating information asymmetry, and optimizing the market environment. It has the potential to greatly enhance and address economic development challenges in the Central and Western regions, providing greater development potential and space for enterprises in these less marketized regions. An indicator variable, "Area," is set to 1 if the company is located in the Eastern region, 2 for the Central region, and 3 for the Western region. After constructing the interaction term between the regional variable (Area) and digital transformation (Digit), Model (2) is tested. The results are presented in Table 4, column (1). It is evident that the regression coefficient for Area is significantly negative at the 1% confidence interval, indicating that as the level of marketization increases, the overall factor productivity of enterprises also increases. Furthermore, the regression coefficient for the interaction term, Area*Digit, is significantly positive at the 1% level, indicating that the impact of the digital economy in empowering is notably greater in the west and middle territories compared to the Eastern territories.

Table 4. Heterogeneity analysis results.

	(1) GTFP	(2) GTFP	(3) GTFP
Digit	0.0403*** (40.6720)	0.0456*** (87.2371)	0.0916*** (12.9547)
*Area *Digit*	0.0040*** (6.4731)		
Area			
*Z *Digit*		0.0051*** (4.8426)	
Z		-0.0089*** (-2.9092)	
*Size *Digit*			-0.0020*** (-6.4063)
Size			0.0372*** (32.9721)
_cons	0.5152*** (30.0303)	0.4963*** (30.2737)	0.3617*** (13.9330)
Control variable	Yes	Yes	Yes
Enterprise *FE*	Yes	Yes	Yes
Year *FE*	Yes	Yes	Yes
N	35305	37525	37525
R^2	0.7139	0.7055	0.7034
Adj. R^2	0.7139	0.7054	0.7033

Note: *, ** and *** represent the significance levels of 10%, 5% and 1%, respectively; The corresponding T-values are in parentheses.

4.3.2. Industry Heterogeneity

Due to the unique characteristics of heavily polluting industries, digital transformation may have more profound effects on their production methods, resource utilization, and environmental impact. The determination of heavily polluting industries aligns with the "Draft for Solicitation of Comments". To delve into the impact of digital transformation on the GTFP of heavily polluting industries, this study introduces a variable, Z, denoting whether a company operates within an industry with significant environmental impact (assigned a value of 1) or not (assigned a value of 0). An interaction term is then created by multiplying the heavily polluting industry variable (Z) with digital transformation (Digit) and subjected to testing. The results are presented in Table 4, column (2). It is evident that the regression coefficient for Z*Digit is significantly positive at the 1% level, indicating that compared to non-heavily polluting industries, the influence of digital transformation on the GTFP of industries with significant pollution is more noticeable.

4.3.3. Size Heterogeneity

To delve into the effect of digital transformation on enterprises' overall productivity. Of different sizes, this study establishes an interaction variable between firm size (Size) and digital transformation (Digit) for testing. The results are presented in Table 4, column (3). It is evident that the regression coefficient for the interaction term Size*Digit is significantly negative at the 1% level. This implies that digital transformation is more favorable for enhancing GTFP in large enterprises.

The main reason for this observation lies in the favorable operational conditions of large-scale enterprises, with strong financing capabilities and clear internal divisions, providing ample human, material, and financial resources for the promotion and utilization of digitalization. Additionally, large-scale enterprises often have dedicated research and development departments engaged in learning and utilizing digital technology for green innovation activities. They have more abundant research and development funds and personnel, which facilitates the output of green innovation. Innovation activities typically involve greater risks, but the comprehensive operational models and multidimensional production systems of large-scale enterprises provide them with relatively strong financial strength and risk resistance. While achieving stable operations, large-scale enterprises are more inclined to enhance their market competitiveness through innovation, thereby driving the development of digital transformation.

Large-scale enterprises possess greater brand influence, making them more likely to receive government subsidies and consumer attention, thereby promoting corporate social responsibility. Therefore, compared to small-scale enterprises, digital transformation is more favorable for fostering the enhancement of GTFP in large enterprises.

5. Mechanism Analysis

In this section, we empirically examine the indirect impact mechanisms between digitization and GTFP using green innovation and supply chain efficiency as mediating variables (M). The mediation effect models are as follows:

$$Lngtfp = \beta_0 + \beta_1 Digit_{it} + \sum \gamma CV_{it} + \sum Company + \varepsilon_{it} \quad (2)$$

$$M_{it} = \alpha_0 + \alpha_1 Digit_{it} + + \sum \gamma CV_{it} + \sum Company + \varepsilon_{it} \quad (3)$$

5.1. Mediation Effect of Green Innovation (EnvrPat)

By constructing green innovation (EnvrPat) as a mediating variable, reflecting the level of a company's green innovation, Table 5 in column (2) reports the impact of enterprise digitization on green innovation. The coefficient for digitization is significantly positive at the 1% level, indicating that enterprise digitization can stimulate green innovation activities. Digitization enhances a company's technological application capabilities, reinforcing innovation awareness and research and development capabilities. This prompts the company to increase technology innovation investment,

engage in more green autonomous innovation activities, and enhance GTFP. Hypothesis 2 is thus supported.

Table 5. Mediation effect of green innovation.

	(1) GTFP	(2) EnvrPat	(3) Stock_day
Digit	0.0164***	0.0233***	-0.0632***
	(21.1425)	(4.0672)	(-12.4358)
_cons	-0.0958***	-1.0293***	3.6151***
	(-2.8953)	(-4.0679)	(20.1030)
Control variable	Yes	Yes	Yes
Enterprise *FE*	Yes	Yes	Yes
Year *FE*	Yes	Yes	Yes
N	37525	37525	37201
R^2	0.8268	0.0196	0.0660
Adj. R^2	0.8268	0.0193	-0.0473

Note: *, ** and *** represent the significance levels of 10%, 5% and 1%, respectively; the corresponding T-values are in parentheses.

5.2. Mediation Effect of Supply Chain Efficiency

To explore the transmission mechanism of supply chain efficiency on the impact of digitization on GTFP, this study constructs inventory turnover days (Stock_day) to reflect supply chain efficiency, with a decrease in inventory days indicating an improvement in supply chain efficiency. The results in Table 5, column (3), indicate that the digitization coefficient is -0.0632 and is significant at the 1% level, suggesting that enterprise digitization can significantly reduce inventory turnover days, thereby enhancing supply chain efficiency. Enterprise digitization transforms internal processes into business intelligence and stimulates digital potential through new business models. This facilitates rapid and convenient data transmission between upstream and downstream enterprises, alleviating information asymmetry in the market. It establishes real-time data sharing and collaborative decision-making among enterprises, improving supply chain efficiency. This, in turn, achieves precise matching of supply and demand and the shared utilization of resources, promoting green supply chain management and innovation. Consequently, it fosters the increase in GTFP, supporting the validation of Hypothesis 3.

6. Conclusion and Recommendations

Drawing from data on China's A-share listed companies spanning from 2007 to 2022, this research extensively uncovers how enterprise digitization influences the GTFP, its heterogeneous performance, and indirect mechanisms. The findings indicate that enterprise digitization contributes to the improvement of GTFP, and this conclusion holds true after a series of robustness tests. Heterogeneity analysis reveals that the beneficial effect of corporate digitization on GTFP is more evident in the Central and Western regions, heavily polluting industries, and large-scale enterprises. Mechanism analysis suggests that enterprise digitization improves GTFP by facilitating green innovation and improved supply chain efficiency.

In light of these discoveries, the following suggestions are put forward:

(1) Governments should strengthen support and guidance for enterprise digitization, with a focus on regional coordinated development. Efforts should be made to vigorously support the construction of digital infrastructure in the Central and Western regions, leveraging the empowering effect of the digital economy to narrow the digital divide. This can be achieved through the provision of fiscal and tax incentives, encouraging enterprises in the Central and Western regions to accelerate their digitization processes.

(2) For heavily polluting industries, the government should increase environmental supervision and support the adoption of digital technology in these sectors. Establishing stricter environmental

standards and emission regulation systems, incentivizing companies to optimize production processes through digital means, and reducing adverse environmental impacts are crucial.

(3) Tailored policies should be introduced for large-scale enterprises to better stimulate their potential for digitization. Developing more flexible innovation policies, increasing financial support for digital technology research and development, and encouraging deeper cooperation in supply chain management and green innovation among large-scale enterprises can be effective strategies.

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