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Research on the Effect and Mechanism of Digital Transformation on The Green Total Factor Productivity of Enterprises

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Abstract: This paper investigates the impact of digital transformation on firms' green total factor productivity (GTFP) and its mechanism. Based on the data of Chinese A-share listed companies in Shanghai and Shenzhen from 2007 to 2022, this paper finds through empirical model analysis that digital transformation has a positive contribution to corporate green total factor productivity. The findings show that digital transformation significantly enhances firms' green total factor productivity, and this conclusion remains robust after considering endogeneity issues. In addition, this paper finds that equity concentration has a negative moderating effect on the relationship between digital transformation and green total factor productivity, suggesting that excessive equity concentration may be detrimental to the enhancement of firms' green productivity. Based on the findings, this paper proposes that the government should formulate supportive policies, strengthen policy guidance and improve regulatory mechanisms to promote the synergistic promotion of digital transformation and green development of enterprises. The findings provide theoretical support and practical guidance for enterprises to achieve green sustainable development in the process of digital transformation.

Keywords: Digital transformation; green total factor productivity; equity concentration.

1. Introduction

On 31 July 2024, the State Council issued the Opinions on Accelerating the Comprehensive Green Transformation of Economic and Social Development, which explicitly proposed to accelerate the synergistic transformation and development of digitalisation and greening. Promote industrial digital intelligence with the deep integration of green, deepen artificial intelligence, big data, cloud computing, industrial Internet and other applications in the power system, industrial and agricultural production, transportation, building construction and operation of the field, the realization of digital technology empowered green transformation. To achieve the goal of a beautiful China enterprise digital transformation is the top priority, and enhance the enterprise green total factor productivity is one of the important ways to build a green China, develop a green economy, and achieve regional sustainable development. According to the data released by the State Administration for Market Supervision and Administration, as of 30 November 2024, the total number of enterprises in the core industries of China's digital economy reached 4,574,100, an increase of 17.99% compared with the end of 2023, showing a rapid growth trend. In terms of industrial classification, the number of enterprises in China's digital technology application industry reached 2,166,900, the number of enterprises in the digital factor-driven industry reached 1,962,500, the number of enterprises in the digital product service industry stood at 236,300, and the number of enterprises in the digital product manufacturing industry stood at 208,200, representing an increase of 17.60 per cent compared with the end of 2023, 19.64 per cent, 16.70 per cent and 8.92 per cent.

So in the context of digital transformation and economic green development, how enterprises can precisely implement business strategies, grasp the transformation dividend and move towards the green development track has become a topic of great concern. Currently, most scholars mainly analyse the role of industrial digital transformation on regional green economic development from the macro dimension, and provide relevant suggestions for enterprises and local governments accordingly, however, there is a lack of research that explores the intrinsic link between enterprise digital transformation and green total factor productivity from the micro level.

2. Literature Review

Current research on the measurement of digital transformation of enterprises.Wu Fei (2021) [1], Yuan Chun (2021) [2], and Zhang Shuhan et al. (2023) [3] analysed the annual reports of listed companies by applying Python crawler technology, screened out keywords and their frequency of occurrence related to the digital transformation of the enterprise, and by aggregating and logarithmically converting these frequencies as an indicator of the level of the digital transformation of the enterprise. Secondly, a questionnaire survey is used. He Xiaogang (2019)[4] portrays the degree of enterprise digital transformation by asking the percentage of employees using computers in the enterprise, and Hu Qing (2020)[5] whether the enterprise carries out the application of digital technology is used to quantify the degree of enterprise digital transformation. However, the sample size of the questionnaire survey is limited and the time span is not long, so the results lack representativeness.Zhai et al. (2022)[6] found that digital transformation can significantly improve enterprise performance by reducing costs, improving enterprise operational efficiency, and promoting enterprise innovation.ChengYiran et al. (2023)[7] found that the digital transformation of enterprises in the real economy can significantly improve the performance of enterprises through increasing working capital turnover, improving human capital structure and reducing financing constraints.Barragan K (2024)[8] proposed a simplified one-dimensional digital

maturity path to estimate the stages of digital transformation in SMEs.

In addition, from the research related to digital transformation on green total factor productivity. Yao Shujun et al. (2022) [9] demonstrated through a questionnaire that smart information interconnections can enhance environmental performance by strengthening information sharing and firms' green governance capabilities. Shin Ho and Tan Weijie (2022)[10]found that digitalisation can work for firms in terms of both quantity and quality of green innovation. Guo Feng et al. (2023)[11] found that enterprise digital transformation promotes both quantitative and qualitative green technological innovation in enterprises by optimising human capital structure and enhancing the level of cooperation between industry, academia and research. Zeng, Qingfen and Liao, Hongtao (2023)[12] found that digital development can achieve pollution reduction and emission reduction through the mechanism of 'cost reduction and efficiency enhancement. Liu Wenjun (2023)[13] argued that digital transformation by promoting green technology innovation Yu Zhiye (2024)[14] found that the overall level of green total factor productivity in China's distribution industry is relatively low, showing a high level in the east, the distribution characteristics of the central and western parts of the country is low, and the industrial agglomeration of the digital economy plays a positive regulating role in the impact of green total factor productivity in the distribution industry. Shi Hong (2024)[15] found that digital transformation can promote green innovation of enterprises through improving human capital level, and media attention plays a positive moderating role in this realisation path.Shang Y (2023)[16] argued that digital transformation of enterprises can significantly reduce the intensity of carbon emissions by improving technological innovation, internal control and environmental disclosure capabilities.Han J (2023)[17] found that digital transformation can enhance GTFP of heavy polluters by promoting green innovation, improving management efficiency, and reducing external transaction costs.In addition, the enhancement effect of digital transformation on GTFP of heavy polluters is more obvious in the samples of non-state-owned enterprises, non-high-tech industries, and the eastern region.Lyu Y (2024)[18] argued that digital economy can significantly reduce carbon emission intensity by means of transmission channels of technological innovation, industrial structure optimisation and resource mismatch to enhance green total factor productivity.

Although the relationship between digital transformation and green total factor productivity has been widely explored by academics, few studies have analysed the specific impact of enterprise digital transformation on green total factor productivity in depth from the micro perspective of enterprises. Based on this, this study aims to explore the role of digital transformation on green total factor productivity from the perspective of micro enterprises under the dual influence of green technological innovation and government environmental subsidies. Through detailed research and analyses, this study will provide practical and targeted development suggestions for the strategic decision-making of enterprises and the policy formulation of local governments, with a view to helping enterprises to achieve sustainable development in the wave of the new era and promoting the green prosperity of the regional economy.

3. Theoretical Research and Hypothesis Development

Digital transformation reflects an enterprise's adoption and in-depth application of digital technological innovation, the core of which lies in the use of digital technology embedded in the enterprise's operational processes and the construction of intelligent feedback and optimisation systems. This transformation promotes the reshaping of the core competitiveness of enterprises by achieving comprehensive quantification and traceability of production and operation activities. In the production chain, digital transformation realises real-time monitoring and accurate management of the production process through technical means such as data analytics, IoT and big data. This process significantly improves the efficiency and precision of resource use. Through the application of intelligent equipment and production lines, enterprises are able to control the input of raw materials more accurately, reduce resource waste and energy consumption, and thus reduce carbon and pollution emissions. This not only promotes the development of green production, but also directly enhances green total factor productivity. It should be stressed that green total factor productivity not only includes capital and labour in the traditional sense, but also covers the efficient use of resources and the minimization of environmental impact. At the same time, digital technology provides enterprises with more accurate decision support systems to help them implement green transformation and sustainable development at the strategic level. For example, by using digital tools to simulate production processes and resource allocation options, companies can choose the optimal low-carbon development path. This intelligent decision-making mechanism not only significantly improves production efficiency, but also effectively reduces environmental burdens, thus continuously promoting green total factor productivity growth. In addition, digital transformation also plays an important role in promoting upstream and downstream synergy in the industrial chain, helping to promote the construction of green supply chains. With the support of digital technology, enterprises are able to share green innovations with suppliers, customers and partners, optimise resource allocation and logistics management, and further reduce resource consumption and emissions. This synergistic effect not only improves the efficiency of the whole industrial chain, but also provides an important guarantee for the improvement of green total factor productivity. Based on the above analysis, this paper proposes the following research hypotheses.

Hypothesis H: The degree of digital transformation can positively enhance green total factor productivity.

4. Research Design and Statistical Sample

4.1. Sample Selection:

This paper intends to select 2007-2022 Shanghai and Shenzhen A-share listed companies as samples and conduct the following treatment:(1) ST∗, ST, and delisted companies are excluded; (2) some of the missing data are filled in by linear interpolation, and the samples of companies with too much missing data are excluded; (3) all continuous variables are subjected to a 1 per cent tail reduction before and after. Relevant data are obtained from Cathay Pacific (CSMAR) and Wind database.

4.2. Research Design

4.2.1. Variable Selection

(1) Explained variables

Green total factor productivity (*Digital*). Green Total Factor Productivity (*Gtfp*) is developed on the basis of traditional Total Factor Productivity. When measuring green total factor productivity, we not only consider the promotion effect of traditional factors of production and technological innovation on economic growth, but also need to take energy consumption and environmental impact factors into account. In this paper, the SBM directional distance function based on non-expected output and the GML index are chosen as the measurement methods by drawing reference from and comparing and analysing the existing studies on the measurement methods of green total factor productivity. See Table 1 for details.

Table 1. Relevant measures of green total factor productivity

Level 1 indicators	Secondary indicators	Meaning of the indicator
Absorbed	capital factor	Net fixed assets
	Labour Factor	Number of employees
	Energy factor	Industrial electricity consumption in the city where the enterprise is located is converted according to the proportion of the enterprise's employees in the employment of urban personnel in the city.
Yield	Desired output	Main business income
		Sulphur dioxide emissions
	Undesired output	Industrial wastewater emissions
		Industrial smoke and dust emissions

(2) Explanatory variables

Digital transformation (*Digital*). Drawing on Wu Fei (2021) [1] and others, it is measured as the natural logarithm of the total word frequency of digital transformation keywords in the annual reports of enterprises plus one.

(3) Other control variables

Enterprise size (*Size*): the natural logarithm of total assets+1, in general, the larger the enterprise size, the more conducive to the improvement of green total factor productivity; gearing ratio (*Lev*): measured as the ratio of total liabilities to total assets at the end of the period;corporate profitability (*Roa*) net profit/average shareholders' equity, the stronger the profitability of the enterprise, the more financial resources to invest in the development of the improvement of green total factor productivity; Shareholding concentration(*Herf*): the proportion of shares held by the first largest shareholder plus 1 to take the natural logarithm of the representation; industry(*Ind*)and region(*area*):the industry and region where the enterprise is located in accordance with the treatment of dummy variables. See Table 2 for variable descriptions and definitions.

Table 2. Variable definitions and descriptions

Variable Type	Variable Name	Variable Symbol	Variable Definition
Explained Variables	Green Total Factor Productivity	*Gtfp*	SBM-DDF Model
Explanatory variables	Digital transformation of enterprises	*Digital*	Natural logarithm of digitised keyword frequency+1 in annual reports
Other control variables	Firm size	*Size*	Natural logarithm of total assets + 1
	Corporate earnings	*R*oa	Net profit/average shareholders' equity
	Shareholding Concentration	*H*erf	Natural logarithm of the first largest shareholder's shareholding example + 1
	trade	*Ind*	Industry dummy variables
	district	*A*rea	Area dummy variables

4.2.2. Modelling

(1) Fixed effects model

Construct a time and individual double-fixed fixed-effects model to study the direct impact of digital transformation on the enterprise's green total factor production retention, and the model is set as follows:

$$Gtfp_{i,t} = \delta_0 + \delta_1 Dig_{i,t} + \delta_2 \sum_{j=2}^{n} X_{i,t} + firm + year + industry + \varepsilon_{i,t}$$

where the explanatory variable $Gtfp_{i,t}$ denotes the green total factor productivity of firm i in year t, and the core explanatory variable $Dig_{i,t}$ is the degree of digital transformation of firm i in year t; $X_{i,t}$ denotes the full text control variables; firm, year, and industry denote the firm, year, and industry fixed effects, respectively; and $\varepsilon_{i,t}$ is is a random disturbance term.

Table 3. Descriptive statistics

Variable Name	Obs	Mean	standard deviation	Max	Min
Gtfp	20,160	0.9430225	0.1265279	1.175966	.7200288
Digital	20,160	0.924944	1.2067	5.010635	0
Size	20,160	22.39334	1.532036	28.29815	0
Roa	20,160	0.221474	2.652489	120.747	-60.05662
Herf	20,160	3.468447	0.4690083	4.510704	0.2517699

5. Analysis of Empirical Results

5.1. Benchmark regression analysis

This study constructs a fixed-effects regression model based on 20,160 observations, with the sample covering 1,263 A-share listed companies, and the number of observations per company ranges from 14 to 16, with an average of 16 observations, ensuring the balance and reliability of the data. After controlling for other relevant variables and individual fixed effects, the regression coefficient for the degree of digital transformation is 0.0554 (standard error = 0.0008), with a t-value of 67.79 and significant at the 1% significance level (P≈0). This result indicates that for every unit increase in the degree of digital transformation, green total factor productivity increases by 0.0553 units on average. This result supports the research hypothesis H that digital transformation of firms can significantly increase their green total factor productivity.

It is worth noting that the regression coefficient of shareholder centralisation is -0.0565 (standard error = 0.0028), with a t-value of -19.79, which is significant at the 1% level of significance (p≈0). This negative relationship indicates that for every unit increase in shareholder centralisation, green total factor productivity decreases by 0.0565 units on average. This result suggests that the significant negative impact of shareholder concentration on green total factor productivity implies that excessive equity concentration may be detrimental to the green productivity of firms.

In addition, the regression results of other control variables also show statistical significance, and the direction of their coefficients is basically consistent with the theoretical expectations, which further enhances the credibility of the model estimation results. Overall, the benchmark regression results provide strong empirical support for the research hypotheses, as well as new empirical evidence for understanding the relationship between corporate digital transformation, corporate governance and green total factor productivity.

Table 4. Baseline regression results

Variable Name	Coefficient	Standard Deviation	T	P>|t|	[95% conf . interval]	
Digital	0.0554	0.0008	67.79	0.000	0.0537	0.0569
Size	0.0635	0.0008	75.89	0.000	0.0618	0.0651
Roa	0.0009	0.0003	2.85	0.000	0.0003	0.0016
Herf	-0.0565	0.0028	-19.79	0.000	-0.3739	-0.0508

5.2. Endogeneity test

The regression results based on two-stage least squares (2SLS) are shown in Table 5, which indicate that digital transformation (dig) has a significant positive impact on the green total factor productivity (gtfp) of enterprises, and the validity test of the instrumental variables supports the rationality of the model.

In the first stage regression, the regression coefficient of the instrumental variable iv2 with digital transformation (dig) is 0.9008 (standard error = 0.0144), and the t-value is 62.58, which is significant at the 1% significance level (P = 0.000), indicating that there is a strong correlation between the instrumental variable iv2 and the endogenous variable digital transformation. In addition, the regression coefficients of the control variables firm size (size) and firm age (helf) were 0.0927 (t=17.13, P=0.000) and -0.2234 (t=-13.48, P=0.000), respectively, which were both significant at the 1% level of significance. The F-statistic for the first-stage regression is 2004.51, which is much larger than the empirical critical value of 10, indicating that there is no weak instrumental variable problem and that the choice of instrumental variables satisfies the relevance condition.

In the second-stage regression, the regression coefficient of digital transformation (dig) is 0.2433 (standard error = 0.0039), with a z-value of 62.17, which is significant at the 1% significance level (P = 0.000), indicating that for every unit of improvement in digital transformation, the firm's green total factor productivity increases by 0.2433 units on average. This result further validates the positive contribution of digital transformation to green total factor productivity. The regression coefficients of the control variables enterprise size (size) and enterprise age (helf) are -0.0215 (z=-14.34, P=0.000) and 0.0531 (z=12.41, P=0.000), respectively, which are both significant at the 1% level, and the signs are consistent with theoretical expectations.

The instrumental variable exogeneity test has a statistic of 4557.42 (P=0.000), indicating that the choice of instrumental variables satisfies the exogeneity condition. The two-stage regression results are consistent with the benchmark regression results in terms of coefficient sign and significance level, further confirming the robustness of the benchmark regression results. This result provides more reliable evidence to support the causal relationship between digital transformation and green total factor productivity.

5.3. Robustness Tests

5.3.1. Lagged explanatory variables

In order to test the robustness of the model, a certain lag in the effect of digital transformation is taken into account. Therefore, in order to mitigate the biased estimation results caused by reverse causality, the digital transformation with one period lag is regressed instead of the explanatory variables. As shown in Table 5, the coefficient of digital transformation with one period lag on enterprises‘ green total factor productivity is significantly positive, which indicates that after mitigating the endogeneity problem caused by reverse causality by lagging one period of the explanatory variables, digital transformation still has a significant positive effect on the improvement of enterprises’ green total factor productivity.

Table 5. Robustness test result

Variable Name	Coefficient	Standard Deviation	T	P>|t|	[95% conf . interval]	
Digital	0.0535	0.0008	66.40	0.000	0.0520	0.0551
Size	0.0623	0.0009	72.04	0.000	0.0606	0.0640
Roa	0.0007	0.0003	2.05	0.000	0.0000	0.0014
Herf	-0.0518	0.0029	-18.04	0.000	-0.0574	-0.0462

6. Conclusions and Recommendations

Digital transformation builds a strong technological foundation for the green development of enterprises and injects a strong impetus for the sustainable development of enterprises. Based on the data of listed companies from 2007 to 2022, this paper verifies through scientific empirical research that digital transformation has a significant positive impact on enhancing enterprises' green total factor productivity, thus strongly supporting the relevant hypotheses. Further, this paper adopts the lagged explanatory variables and instrumental variables method to test the robustness of the model and analyse the endogeneity issues, and the results show that the conclusions are still robustly established even after considering these potential issues. In addition, it is found that equity concentration negatively moderates the relationship between digital transformation and green total factor productivity, a finding that provides an important reference for business owners and corporate strategy makers, and helps firms to avoid the negative impact of over-concentration of equity on the improvement of green total factor productivity in the process of digital transformation, so as to better achieve the green development goals of firms.

Based on the above conclusions, there are the following policy insights: (1) Formulate supportive policies: the government should introduce relevant policies to encourage enterprises to accelerate digital transformation and green technological innovation. For example, special subsidy funds should be set up to provide financial subsidies to enterprises that carry out digital transformation and green technology innovation; tax incentives should be provided to reduce the tax burden on enterprises in terms of the purchase of digital equipment and the research and development of green technologies. (2) Strengthen policy guidance: The government should strengthen policy guidance for enterprises and promote them to combine digital transformation with green development strategies. By formulating green industry development plans and digital transformation guidelines, it should guide enterprises to clarify their development direction and improve their enthusiasm and initiative in digital transformation and green development. (3) Improve the regulatory mechanism: The government should strengthen the regulation of enterprises' environmental behaviour, establish a sound environmental information disclosure system, and require enterprises to regularly disclose green total factor productivity and other relevant indicators, so as to improve the transparency of their environmental behaviour. At the same time, it should strengthen the supervision of data security and privacy protection in the process of enterprise digital transformation to guarantee the smooth progress of enterprise digital transformation.

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