Academic Journal of Management and Social Sciences
ISSN: 2958-4396 | Vol. 9, No. 1, 2024

The Impact Analysis of the Digital Economy on Green Total Factor Productivity in the Yangtze River Delta Urban Agglomeration

Jilai Zhu, Gan Liu

Finance Department, Hangzhou Dianzi University, Hangzhou, Zhejiang, China

Abstract: The deep integration of digitalization and greening is a driving force for promoting high-quality economic development. The rapid development of the digital economy empowers green innovation, and the Yangtze River Delta urban agglomeration, as the most developed region in China's economy, carries an important mission for the future economic and social development of China. Clarifying the differences and influencing factors of digital economy and green total factor productivity (GTFP) among different cities within the Yangtze River Delta urban agglomeration is of great significance for formulating regional and national green development policies, achieving regional coordinated development, and environmental sustainability. This paper takes the impact of digital economy development on changes in GTFP as the starting point. Through the analysis of innovation efficiency, a theoretical model is established to reveal the internal mechanism by which digital economy development promotes GTFP. The research results show that digital economy development significantly promotes the improvement of GTFP, with greater impacts on large and medium-sized cities, regions with higher productivity levels, and regions with a more advanced industrial structure. Additionally, the internal mechanism test results indicate that digital economy development enhances GTFP by improving regional innovation efficiency and resource allocation efficiency.

Keywords: Digital Economy; Green Total Factor Productivity; Mediating Effect; Digital Economy Environment; Green Transformation.

1. Introduction

In recent years, the digital economy, as an emerging economic paradigm, has experienced rapid growth globally. China, as the world's largest developing country, is undergoing a fast-paced rise in the digital economy. By 2023, the scale of China's digital economy has surpassed 50 trillion yuan, accounting for over 40% of its GDP, making it a key driver of economic growth. The widespread adoption and application of digital technologies have not only transformed the operational models of traditional industries but also fostered the emergence of new business models. However, this mode of economic development has revealed certain drawbacks, such as high input with low efficiency, excessive energy consumption, severe environmental pollution, and ecosystem degradation, which have constrained economic and social development, especially during the processes of industrialization and urbanization.[14][15] These challenges further underscore the significance of green development.

In response, the Chinese government has introduced a series of policies aimed at promoting green development. For example, the 2016 *National Green Development Plan* outlined the direction for a green economy, while the 2020 *Carbon Peak Action Plan* emphasized the importance of reducing carbon emissions. These policies have provided strong support for advancing the green transformation of the economy. By promoting the adoption of green technologies and clean energy, green development not only improves economic efficiency but also protects natural resources, enhances ecosystems, and fosters comprehensive social progress.

In this context, green total factor productivity (GTFP) serves as a critical indicator for assessing the balance between economic development and environmental protection, highlighting the importance of sustainable development. The digital economy, through technological innovation and informatization, can optimize resource allocation, improve production efficiency, and reduce the negative impacts on the environment. The application of digital technologies in optimizing energy use, promoting cleaner production, and facilitating the circular economy is transforming traditional production and consumption patterns. These technological applications not only help enhance GTFP but also drive the economy toward a green and sustainable trajectory.

Therefore, studying the impact of the digital economy on GTFP is crucial for China's pursuit of healthy and sustainable development. Such research can provide policymakers with scientific evidence to help formulate more effective industrial and environmental policies, encouraging cities to emphasize the application of green technologies during their digital transformation. Furthermore, the findings can offer new theoretical perspectives to the academic community, enriching the research on the interplay between the digital economy and sustainable development.

2. Literature Review

Research on the relationship between the development of the digital economy and industrial green total factor productivity (GTFP) is relatively limited and can be summarized in two main aspects:

First, from the perspective of the mechanism through which internet development impacts GTFP. The improvement of GTFP depends on the ability to develop and adopt new technologies, namely technological progress[1] and the efficiency of existing technologies[2]. Hence, innovation efficiency can influence GTFP by affecting both technological efficiency and progress. The development of the digital economy has broken the spatial and temporal

limitations on knowledge accumulation and information dissemination, fostering the integration and processing of information. In the process of information sharing and dissemination among different individuals, varying degrees of information accumulation occur, thereby driving societal technological progress[3]. Guo Jiatang and Luo Pinliang explored the ways internet development promotes technological progress by examining internet technologies, platforms, and thinking. They innovatively proposed that the establishment of internet platforms can accelerate research and development (R&D) speeds, increase the success rate of R&D, and thus promote technological progress[5]. Han Xianfeng et al. found that the rapid development of the internet significantly improved regional innovation efficiency and human capital accumulation in China, accelerated financial development, and promoted industrial upgrading, indirectly enhancing regional innovation efficiency. In a study of the mechanisms by which the internet promotes industrial GTFP[6], Lu Fucai et al. (2021) discovered that the internet has a significantly positive effect on industrial GTFP improvement. Similarly, Zhu Xi'an and Ma Yingge (2022) found that digital economy development enhances GTFP by improving regional innovation efficiency[4].

Second, in terms of the relationship between digital economy development and GTFP, Wu Jing et al. (2021) used a spatial Durbin model and a panel threshold model to reveal that digital economy development has a significantly positive effect on green development. Their findings also indicated that GTFP exhibits significant spatial spillover and temporal dependency, with stronger positive effects in central and western regions than in eastern China[8]. Xiao Yuanfei et al., through empirical analysis, found that digital economy development contributes to improving regional GTFP, and that the eastern region benefits more significantly from digital dividends compared to the western region[9]. Similarly, Zhou Xiaohui et al. (2021) argued that digital economy development promotes GTFP growth with notable regional differences. They found that the digital economy significantly enhances the GTFP of central cities while its "siphon effect" hinders the GTFP improvement of peripheral cities. Additionally, the development of the digital economy has a "structural" promotion effect on GTFP, with digital industrialization and industrial digitization serving as long-term drivers of GTFP improvement[10]. Chen Bing and Wang Weilong (2021) pointed out that both internet development and industrial structure upgrading significantly promote GTFP growth. Furthermore, the synergistic effects of internet development and industrial structure upgrading also play a significant role in enhancing GTFP. Their findings revealed that the impact of internet and industrial structure upgrading on GTFP varies significantly across different fields, innovation policies, and resource types.[11]

Upon reviewing the relevant literature, this paper finds that existing studies mainly focus on exploring the mechanisms through which factors such as technological innovation, institutional environment, and R&D investment influence GTFP in the context of the digital economy. However, various unique endowments and conditions, such as the level of digital economy development and the overall digital economy environment in different provinces, cities, and autonomous regions, also play a significant role in the digital economy's impact on GTFP. Current research has yet to simultaneously consider both the level of digital economy development and the differences in the comprehensive environment across regions. Therefore, further expansion and refinement of research in this area are needed. Additionally, in-depth exploration of regional differences can provide more targeted guidance for policymakers, helping different regions optimize their digital economy development strategies, improve overall GTFP levels, and promote sustainable economic growth. By combining specific case studies and empirical analysis, it will be possible to uncover the unique dynamics and mechanisms across regions, providing valuable insights for future academic research and practical applications.

3. Theoretical Analysis and Research Hypotheses

The development of the digital economy has infused new vitality into traditional industries by enhancing technological innovation capabilities and optimizing resource allocation, thereby promoting green development. The digital economy plays a direct and significant role in improving green total factor productivity (GTFP), aligning with the requirements of sustainable economic and environmental development. The digital economy, characterized by data as a key production factor, exhibits features such as speed, intelligence, networking, and directness. These characteristics enable it to overcome geographical and temporal constraints, accelerate information transmission, reduce distortion during the transfer of information[23], efficiently process large-scale data, and quickly match the needs of supply and demand, thereby addressing the inefficiency of traditional search and matching processes. Additionally, the digital economy can largely eliminate information asymmetry and significantly reduce transaction costs, leading to improved resource allocation efficiency and enhanced productivity[23].

Moreover, the digital economy is inherently sustainable, effectively curbing the excessive consumption of tangible resources—especially energy—seen in traditional industrial production. By facilitating the reallocation of existing production factors and improving their utilization efficiency, the digital economy supports energy conservation and emission reduction, ultimately reducing environmental pollution and advancing green development in line with the principles of sustainability. Furthermore, digital technology can integrate with production factors, driving the transition of industries toward more technology- and capital-intensive sectors. This shift promotes the digital and green transformation of enterprises, which in turn boosts GTFP. According to Wu Jing et al., the digital economy also improves GTFP by enhancing ecological regulation services and optimizing the environmental governance system. As "Internet + Government Services" continues to advance, the speed of information flow within environmental protection systems increases, enabling individuals, businesses, and governments to access and utilize relevant information more efficiently.[8]

Theoretically, the digital economy can influence GTFP through various channels. But can the rapidly growing digital economy in the Yangtze River Delta region effectively promote GTFP in practice? To address this question, this paper proposes the following hypothesis:

Hypothesis 1: The development of the digital economy significantly promotes GTFP improvement.

Under the digital economy, Zhang Xinwei et al. found that new technological paradigms continually drive the transformation and upgrading of innovation models[16]. The digital economy can disrupt the traditional R&D models of manufacturing, overcoming bottlenecks in the innovation chain and integrating R&D efforts. Jiao Yong argued that technological, model, business, and institutional innovations fostered by the digital economy inject new vitality into manufacturing[17]. Wan Lunlai and Zhu Qin found that technological innovation significantly promotes green industrial development and enhances GTFP[18]. Moreover, the development of the digital economy accelerates the marketization of factors, reduces labor misallocation, facilitates the movement of technology through data elements, and promotes the marketization of products and services. By reducing information asymmetry, it increases market competitiveness and fairness, thus improving the efficiency of resource allocation. Higher marketization levels can mitigate the environmental pollution caused by industrial agglomeration and enhance the strength of environmental regulations, thereby improving GTFP[19]. The digital economy, through data as a production factor, enhances the coordination among factors, expands the boundaries of industrial division of labor, and promotes the transformation of traditional industries.

Furthermore, the digital economy breaks the diminishing returns principle of the industrial economy era, continuously improving industrial value creation and driving industrial structure upgrading. The transformation and upgrading of industrial structures optimize factor allocation, direct production factors toward high-growth sectors, and promote technological upgrading, which reduces pollutant emissions and enhances GTFP. The development of the digital economy also raises the demand for human capital, which can optimize human capital structures through "technological complementarity" and "scale expansion" effects, driving the upgrading of human capital[21]. Innovative human capital, with its inherent creativity, engages in independent and imitative innovation, thereby advancing green technological innovation, application, and diffusion. This process increases energy efficiency and reduces pollutant emissions, ultimately improving GTFP[20].

Based on the above analysis, the following hypothesis is proposed:

Hypothesis 2: The development of the digital economy in the Yangtze River Delta region enhances the GTFP of the manufacturing sector by promoting technological innovation and improving resource allocation efficiency.

4. Research Design

4.1. Model Construction

Based on the exploration of the relationships and theoretical mechanisms discussed above, this paper constructs the following regression model:

$$GTFP_{it} = \alpha + \beta_1 \mathrm{DE}_{it} + \gamma_1 CVs_{it} + \delta_t + \theta_p + \varepsilon_{it} \quad (1)$$

The dependent variable $GTFP_{it}$ represents the green total factor productivity (GTFP) index for region i in year t, while the independent variable DE_{it} denotes the level of digital economy development in region i in year t. Control variables CVs_{it} are included to account for factors that may impact the model due to fluctuations in the economic cycle, the introduction of relevant policies, and unexpected events that vary over time and across regions. To mitigate the effects of these time-varying δ_t and region-specific factors on the model, fixed effects for time δ_t and region θ_p are incorporated, and the random disturbance term is denoted as ε_{it} .This model aims to analyze how digital economy development influences the green total factor productivity across different regions over the specified period.

4.2. Selection and Measurement of Variables

This paper selects panel data from 26 major cities in the central cities of the Yangtze River Delta from 2009 to 2021 for empirical analysis. The data mainly comes from the "China Statistical Yearbook", "China City Statistical Yearbook" and the National Bureau of Statistics. Some individual data in some regions are missing, and linear interpolation is used to fill the data.

Explained variables: The measurement of the green total factor productivity index is one of the core links of this article. The DEA model is widely used because it can study multiple inputs and multiple outputs without setting the form of the production function. In the early days, this type of method did not consider non-expected outputs, and the measurement results may be biased. The improved model (SBM) is a non-radial model and cannot handle radial problems; the EMB model can overcome this shortcoming. Considering that the global GML is transitive, this paper chooses the EBM-GML method to measure green total factor productivity. The specific model is as follows:

$$\psi = \min \frac{\xi - \omega_x \sum_{u=1}^{m} \frac{\varpi_u^- s_u^-}{x_{uh}}}{\varphi + \omega_{y_G} \sum_{j=1}^{n} \frac{\varpi_j^+ s_j^+}{y_{Gjh}} + \omega_{y_B} \sum_{z=1}^{l} \frac{\varpi_z^- s_z^-}{y_{Bzh}}} \quad (2)$$

$$\text{s.t.} \begin{cases} X\delta + s_u^- = \xi x_h, u = 1,2,\cdots,m \\ Y_G\delta - s_j^+ = \varphi y_{Gh}, j = 1,2,\cdots,n \\ Y_B\delta + s_z^+ = \varphi y_{Bh}, z = 1,2,\cdots,l \\ \delta \geq 0, s_u^-, s_j^+, s_z^- \geq 0 \end{cases} \quad (3)$$

X, Y_G , Y_B and respectively represent m inputs, n expected outputs and I non-expected outputs; H is the number of decision-making units; $\psi(0 \leq \psi \leq 1)$ is the optimal efficiency value; ϖ_u^-、ϖ_j^+、ϖ_z^- and s_u^-、s_j^+、s_z^- respectively represent the weights and slack variables of the u-th input, j-th output and z-th non-expected output;$\omega(0 \leq \omega \leq 1)$ is an important parameter of the comprehensive radial efficiency value ξ and non-radial slack variables. In this paper, the global efficiency value ψ is used as the industrial green total factor productivity Gy_{it} of each province. The indicator system is shown in the following table:

Explanatory variables: The level of digital economic development. Most scholars have constructed a comprehensive indicator system based on the research purpose. Yang Huimei et al. used the principal component analysis method to construct a measurement index of the digital economy level at the provincial level in my country based on the two dimensions of digital industrialization and industrial digitalization [15]. Ma Zhongdong et al. measured the comprehensive level of China's provincial digital economy from three aspects: digital infrastructure, digital life applications, and digital industry development [26]. The research time span of this paper is 2009-2021. Considering the availability, comparability, and comprehensiveness of data, Yang Chengliang et al. [18] pointed out that the

development of the digital economy depends on digital infrastructure, digital industrialization, and digital development environment. Ten secondary indicators are selected to construct a digital economy development level index. The digital economy development level of 26 core cities in the Yangtze River Delta region is measured using the entropy method. The digital inclusive finance data uses the China Digital Inclusive Finance Index jointly compiled by the Digital Finance Research Center of Peking University and Ant Financial Services Group. The specific indicator system is shown in Table 2

Table 1. Input-output indicators of green total factor productivity

Categories	variables,	measurement method	units
Input variables	Real capital stock	Perpetual inventory method, annual fixed asset investment is deflated using relevant price indices to 2011	100 million yuan
	labor force	Average number of employees	10,000 people
	Energy consumption	Urban electricity consumption	GW
Desired output,	Real GDP	Nominal GDP converted	100 million yuan
undesired output	Industrial sulfur dioxide	Industrial sulfur dioxide emissions	10,000 tons
	Industrial wastewater	Industrial wastewater discharge	10,000 tons
	Industrial smoke powder	Industrial smoke emissions	10,000 tons

Table 2. Evaluation index system of digital economy development level

First level indicator	Secondary indicators	unit	Indicator properties
Digital Infrastructure	Number of Internet users per 100 people	Households/100 people	Positive
	Internet broadband access users	Households/10000 people	Positive
	Number of mobile phone users per 100 people	Households/100 people	Positive
Digital Industrialization	The proportion of employees in computer service and software industry to employees in urban units	%	Positive
	Total telecommunications business	Ten thousand yuan,	Positive
	Digital Financial Inclusion Index	/	Positive
	Postal business volume	Ten thousand yuan,	Positive
Digital Development Environment	R&D Expenditure	Ten thousand yuan,	Positive
	R&D personnel	Ten thousand people	Positive
	Number of students in regular colleges and universities	Ten thousand people	Positive

Control variables: Financial development level (FDL_{it}) is measured by the proportion of RMB deposit balance of financial institutions to GDP, and then its logarithm is taken to express the financial development level; per capita road area (PRP_{it}) is measured by the per capita urban road area, and then its logarithm is taken to express the economic development level; economic development level (EDL_{it}) converts the per capita GDP of each province into the actual value with 2006 as the base period, and then its logarithm is used to express the economic development level; industrial structure (IS_{it}) is measured by the proportion of local tertiary industry GDP; fiscal decentralization (PRE_{it}) is measured by the proportion of local fiscal general budget revenue to local fiscal general budget expenditure.

4.3. Data Description

The data used in this paper are the relevant data of digital economy and manufacturing industry in 26 central cities, provinces, cities and districts in the Yangtze River Delta region from 2009 to 2021. The data sources are the National

Bureau of Statistics, the China Statistical Yearbook, the China Industrial Statistical Yearbook, the China Labor Statistical Yearbook and other yearbooks and the China Carbon Emission Database. The relevant value variables are all based on 2006 as the base period. When calculating the level of digital economic development, some missing data are supplemented by linear interpolation. The descriptive statistics of the main variables are shown in Table 3:

Table 3. Descriptive statistics of variables

variable	Number of observations	average value	Median	Standard Deviation	Minimum	Maximum
GTFP	338	0.582	0.567	0.162	0.261	1
DE	338	0.232	0.214	0.145	0.0100	0.925
FDL	338	0.986	0.948	0.327	0.320	1.840
PRP	338	3.031	3.132	0.416	1.396	3.837
EDL	338	2.417	2.423	0.0480	2.255	2.502
IS	338	0.450	0.450	0.0920	0.234	0.752
PRE	338	0.735	0.737	0.204	0.291	1.116

5. Analysis of Empirical Results

5.1. Baseline Regression Analysis

Table 4. Benchmark regression of digital economy development and green total factor productivity

variable	(1)	(2)	(3)
	GTFP	GTFP	GTFP
DE	0.354***	0.766***	0.624***
	(0.099)	(0.075)	(0.099)
FDL	-0.091***	-0.081**	-0.139***
	(0.034)	(0.037)	(0.046)
PRP	-0.026	0.012	0.000
	(0.018)	(0.030)	(0.030)
EDL	0.995***	-0.159	-0.677**
	(0.214)	(0.197)	(0.275)
IS	0.634***	0.104	-0.038
	(0.164)	(0.107)	(0.134)
PRE	-0.133***	-0.158***	-0.169***
	(0.038)	(0.051)	(0.055)
Constant term	-1.924***	0.874**	2.386***
	(0.475)	(0.425)	(0.697)
Sample size	338.000	338.000	338.000
R2	0.504	0.885	0.892
Region fixed effects	NO	YES	YES
Time fixed effects	NO	NO	YES

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, p represents the significance level, and the statistics in parentheses are

First, the ordinary least squares (OLS) method is used to regress the digital economy development level and green total factors. There are no fixed effects added to the results in column (1) of Table 1. The results show that the estimated coefficient of the digital economy on the green total factor productivity index is 0.354, which is significantly positive at the 1% level (t=0.099). In order to prevent regional factors to have an impact on the model, column (2) adds the regional fixed effects model. The results show that the estimated coefficient of the digital economy on the green total factor

productivity index is 0.766, which is significantly positive at the 1% level (t=0.075). Finally In order to prevent time factors from also affecting the model, time fixed effects are added in column (3). The results are still significant and positively correlated at the 1% level, which means that the higher the level of digital economy development, the green total factors of the region. The changes in productivity will also be higher. For every 1% growth in digital economic development, the green total factor productivity index will increase by 0.624%

5.2. Robustness Test

5.2.1. Solving the Endogeneity Problem

Although the benchmark model controls the variables that may have a confounding effect on green total factor productivity, there may be measurement errors in the digital economic development level indicators, which leads to inaccurate estimation of the effect between the digital economic development level and green total factor productivity. At the same time, green total factor productivity may also affect the level of digital economic development, so the estimation results of the benchmark model may be biased due to endogeneity problems. To this end, this paper seeks suitable instrumental variables to test the robustness of the benchmark model. Drawing on the idea of constructing instrumental variables in existing studies, this paper uses the product of the geographical slope data of each city and the Internet penetration rate to construct instrumental variables. Table 4 reports the regression results of the instrumental variables. The weak IV test results show that the Cragg-Donald Wald F values are all greater than the 10% level critical value of Stock-Yogo; the K-Paark LM statistic of the unidentifiable test rejects the null hypothesis at the 1% level, satisfying the identifiability of the instrumental variable. After considering the endogeneity problem, the regression coefficients of the digital economy on green total factor productivity are significant at the 1% level. The regression results show that the impact of digital economic development on the explained variables is still positive, indicating that after considering possible endogeneity problems, the development of the digital economy still has a positive impact on green total factor productivity.

5.2.2. Addressing Robustness

Table 5. Robustness test results

	（1）	（2）	（3）	（4）
variable	**Instrumental variables**	**Substitution variables**	**Substitution variables**	**Shrinkage**
	GTFP	**GTFP**	**GTFP**	**GTFP**
DE	1.095*** (0.183)		0.693*** (0.096)	0.632*** (0.099)
FDL	-0.121*** (0.045)	-0.165*** (0.048)		-0.140*** (0.046)
PRP	0.034 (0.031)	-0.034 (0.031)		0.001 (0.030)
EDL	-0.462* (0.275)	-0.931*** (0.286)		-0.643** (0.274)
IS	0.072 (0.135)	-0.126 (0.141)		-0.048 (0.134)
PRE	-0.176*** (0.054)	-0.150** (0.059)		-0.169*** (0.055)
NOU		0.004** (0.002)		
Weak IV Test	110.76（16.38）			
Unidentifiable test (P) value	92.499***			
Constant term	1.463** (0.741)	3.295*** (0.717)	0.349*** (0.059)	2.307*** (0.695)
Sample size	338.000	338.000	338.000	338.000
R2	0.884	0.880	0.884	0.892
Region fixed effects	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES

In order to ensure the accuracy of the core conclusions, this article conducts robustness tests from three aspects: first, to

replace the explanatory variables, and choose Internet penetration rate to represent the development level of the digital economy; second, to remove the control variables; third, to perform shrinking processing, this article uses the Yangtze River Panel data of 26 cities in the center of the Delta region from 2009 to 2021. In order to exclude outliers in the explained variables, this article draws on the approach of Guo Feng et al. (2022) [27], this article performs a 1% bilateral shrinkage on the green total factor productivity. deal with. Table 5 shows the results of the robustness test of the digital economy on green total factor productivity in the Yangtze River Delta region. Among them, models (2), (3) and (4) respectively adopt alternative explanatory variables, remove control variables, and shrink the green total factor productivity by 1%. The robustness of the impact of the digital economy on green total factor productivity in the Yangtze River Delta region Testing the results, the results show that the regression coefficient of the digital economy is significantly positive, indicating that the digital economy can significantly improve the green total factor productivity of the manufacturing industryis robust.

5.3. Heterogeneity Analysis

5.3.1. Heterogeneity Exists in Regional Development

This article divides the 26 central cities in the Yangtze River Delta based on the median of their regional GDP. If the regional GDP is greater than the median, they are large and medium-sized cities. If the regional GDP is less than the median, they are small cities. They are grouped. return. From column (1) of Table 6, it can be concluded that the regression coefficient of digital economy on green total factor productivity index in large and medium-sized cities is significantly positive at the 1% level, while it is not significant in small cities. This shows that the promotion effect of digital economy on green total factor productivity index is more obvious in large and medium-sized cities. This may be related to the economic scale and resources. Large and medium-sized cities have gathered more resources and talents, and can better implement and utilize digital technology. technology. In small cities, resources are limited and the application of digital economy is restricted.

5.3.2. There is Heterogeneity in the Level of Productivity Changes

This article refers to the research results of Yang Huimei and Jiang Lu (2021), and uses the median of the green total factor productivity index to divide the level of changes [15]. If the regional green total factor productivity index is greater than the median level of the corresponding year, it is a high-productivity area, otherwise it is a low-productivity area. The regression results in column (2) of Table 6 show that the promotion effect of digital economy development is significantly positive in areas with higher levels of green total factor productivity index, but is not significant in areas with lower productivity levels, and in areas with high productivity The promotion effect is significantly greater than that of low-productivity areas. The test results are basically consistent with the regional grouping. Generally, the green total factor productivity index of large and medium-sized urban areas is higher than that of small cities. Therefore, it is possible that these areas already have the technical foundation and can better integrate digitalization. Tools improve efficiency. In addition, strong innovation capabilities, high resource allocation efficiency, and strong market demand for green products make it easier for digital technology to generate gains. Policy support is also more inclined, further promoting the combination of digitalization and green development.

5.3.3. Heterogeneity Exists in Industrial Organizations

This article measures the advancement of industrial structure by the ratio of the added value of the tertiary industry to the added value of the secondary industry. The grouping of industrial structure is also measured based on the median. The results of the industrial structure grouping in the third column of Table 6 show that the impact of digital economy development on changes in green total factor productivity is significantly positive in areas with a higher proportion of the tertiary industry, but not significant in areas with a higher industrial structure. The green total factor productivity improvement effect is greater. In areas with a high ratio between the tertiary industry and the secondary industry, the impact of the digital economy on green total factor productivity is more obvious. First of all, it is very likely that the tertiary industry (service industry) is usually more flexible and permeable in the application of digital technology. These regions can more easily integrate digital tools to optimize processes, increase efficiency, and drive innovation.

In contrast, regions with lower ratios are likely to rely on traditional manufacturing, have slower digital transformation, and have limited adoption of green technologies. In addition, the digital advantages of the service industry are difficult to give full play to in low-ratio areas, which limits the role of the digital economy in improving green total factor productivity.

5.4. Mechanism Inspection

The above series of tests show that the digital economy can significantly improve the green total factor productivity in the Yangtze River Delta region. Then whether the digital economy's promotion of green total factor productivity is transmitted through channels such as technological innovation and industrial structure upgrading requires further regression verification. Based on theoretical analysis and research hypotheses, this article selects the number of authorized patents per 10,000 people to measure regional innovation efficiency (innoeff). The data comes from the EPS Database China Regional Database. Resource Allocation Efficiency In this article (l) resource allocation efficiency. The effective allocation of resources is an allocation state in which the free flow of factors maximizes social output under the conditions of market mechanisms, while resource misallocation or market distortion means a deviation from this state. Drawing on relevant research by Hsieh and Klenow (2009), Li Qingyuan and Zhang Yinsainan (2021) [24][25], the production function method is used to measure the degree of factor market distortion in each city. The regression results are shown in Table 7.

Table 6. Heterogeneity test results

variable	（1）		（2）		（3）	
	Regional Grouping		GTFP Grouping		Industrial structure grouping	
	Small cities	Large and medium cities	Low	High	Low	High
	GTFP	GTFP	GTFP	GTFP	GTFP	GTFP
DE	0.154	0.369***	0.186	0.524***	0.190	0.593***
	(0.173)	(0.133)	(0.145)	(0.147)	(0.125)	(0.158)
FDL	-0.122**	0.000	-0.113*	-0.175**	-0.094**	-0.019
	(0.059)	(0.065)	(0.057)	(0.071)	(0.046)	(0.102)
PRP	0.030	0.025	0.033	0.009	-0.022	0.034
	(0.038)	(0.043)	(0.035)	(0.053)	(0.031)	(0.054)
EDL	0.076	-0.723	-0.696**	-1.247**	-0.669***	-0.864
	(0.358)	(0.494)	(0.296)	(0.617)	(0.245)	(0.857)
IS	0.337**	-0.491**	0.054	-0.063	0.100	0.334
	(0.169)	(0.203)	(0.152)	(0.235)	(0.150)	(0.287)
PRE	-0.251***	-0.039	-0.029	-0.247**	-0.090*	-0.291**
	(0.071)	(0.093)	(0.059)	(0.108)	(0.050)	(0.142)
Constant term	0.401	2.560**	2.176***	3.922***	2.358***	2.504
	(0.869)	(1.195)	(0.742)	(1.491)	(0.591)	(2.143)
Sample size	169.000	169.000	169.000	169.000	169.000	169.000
R2	0.9146	0.8780	0.7661	0.7691	0.9378	0.8733
Region fixed effects	YES	YES	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES	YES	YES

The regression results show that the digital economy can improve green total factor productivity through promoting technological innovation and improving resource allocation efficiency. Hypothesis 2 has been verified. From the perspective of regression coefficients, the regression coefficient of digital human capital level is the largest and significant at the 1% level, which means that the development of the digital economy requires more technological innovation. At the same time, the development of the digital economy significantly promotes data and other element resources. The flow accelerates the process of factor marketization, reduces resource misallocation and improves the efficiency of market allocation of resources, thereby significantly improving the level of green total factor productivity in the manufacturing industry.

6. Conclusion and Policy Recommendations

Under this severe and complex situation, how to accelerate the realization of an innovative, efficient, energy-saving and environmentally friendly high-quality economic development model is a core issue that needs to be solved urgently in our country. This article empirically analyzes the impact of the digital economy on GTFP on the basis of measuring the development level of the digital economy and GTFP in 26 core cities in the Yangtze River Delta region from 2009 to 2021. The main conclusions are as follows:

First, the green promotion effect of the digital economy exists, significantly promoting the growth of GTFP, and can become a new engine to improve China's GTFP in the new era, indicating that the digital economy is conducive to promoting the process of green development in our country, and this conclusion is based on a variety of robust sex test.

Second, the sub-regional test results show that there are obvious regional differences in the impact of the digital economy on GTFP. Specifically, the development of the digital economy has significantly promoted the growth of GTFP in large and medium-sized cities, but it is not obvious for small cities. In addition, the impact of the digital economy on green total factor productivity has quantile heterogeneity, that is, low-quantile cities The impact of digital economy on total factor carbon productivity is not significant. The impact of digital economy on green total factor productivity in high-quantile cities is significantly positive. At the same time, it has a significant impact on areas with a high degree of advanced industrial structure, while for areas with advanced industrial structure It is not significant in areas with low values.

Third, through demonstration, it is proved that the impact of digital economic development on changes in regional green total factor productivity is transmitted through two paths: improving regional innovation efficiency and mitigating the degree of regional factor mismatch. The widespread application of digital technology provides innovation momentum for regions, gives products digital attributes,

improves product attributes and value, accelerates the integration of production factors, and improves innovation efficiency. In addition, the development of the digital economy can, to a certain extent, reduce the level of regional factor misallocation by improving labor allocation and capital factor allocation.

Table 7. Mediation effect regression results

Variable	(1)		(2)	
	IL	GTFP	RM	GTFP
DE	77.596***	0.535***	0.778***	0.430***
	(22.600)	(0.100)	(0.120)	(0.101)
FDL	-14.411	-0.110**	-0.179***	-0.094**
	(10.519)	(0.045)	(0.056)	(0.045)
PRP	-28.233***	0.030	-0.116***	0.030
	(6.951)	(0.031)	(0.037)	(0.030)
EDL	-229.314***	-0.544**	-0.374	-0.583**
	(62.687)	(0.275)	(0.333)	(0.263)
IS	-27.248	-0.042	-0.640***	0.122
	(30.652)	(0.132)	(0.163)	(0.132)
PRE	-4.639		-0.178***	-0.125**
	(12.641)		(0.067)	(0.054)
IL		0.001***		
		(0.000)		
RM				0.250***
				(0.046)
Constant term	611.518***	1.795**	1.744**	1.950***
	(159.028)	(0.695)	(0.845)	(0.670)
Sample size	338.000	338.000	338.000	338.000
R2	0.871	0.895	0.837	0.902
Region fixed effects	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES

Therefore, this article puts forward the following targeted suggestions:

First, continue to deepen the digital transformation of industries. The development of the digital economy can, to a certain extent, promote the improvement of green total factor productivity. This promotion of economic growth is in line with the concepts and requirements of "green development" at the current stage and is sustainable. At present, for digital industrialization, China already has a series of advanced enterprises and advanced technology support. These industries relying on digital technology have developed rapidly in China in recent years, and some enterprises have reached the international leading level. However, for traditional industries, digital technology has not yet been widely used. Only by continuing to promote the deep integration of traditional industries and digital technology, and realizing the advanced manufacturing base and modernization of the industrial chain can we effectively improve the core competitiveness of my country's real economy.

Second, as the digital economy and the green and low-carbon economy gradually become the two mainstreams of China's social and economic development, all regions must deeply tap their own digital economic development potential and persist in promoting the formation of a new digital economic development pattern. At present, although my country's digital economy is developing relatively rapidly, there is still a lot of room for growth, and the uneven development between regions is obvious. This requires governments at all levels to continue to implement digital infrastructure construction and broaden the application scope of digital elements. At the same time, we must also pay attention to the differences in the development level of the digital economy between regions, promote classification according to the actual economic development conditions of each region, and implement precise policies, so as to give full play to the green promotion effect of the digital economy and help my country's inter-provincial GTFP growth.

Third, innovation drives the development of digital technology. The development of the digital economy can affect the changes in green total factor productivity by improving regional innovation efficiency. The improvement of innovation efficiency is inseparable from the innovation and application of digital technology. Only by continuously expanding innovation and creation in the field of digital technology can we maintain the continuous inflow of talents

in the digital field and continue to The need to expand the digital realm.

Fourth, improve market rules for data elements. The improvement of the development level of the digital economy can alleviate the mismatch of factors and promote the improvement of green total factor productivity. The circulation of data elements and information in the market needs to follow certain rules. How to make data elements in the market while ensuring data security and privacy protection? Adequate flow needs to be regulated by policy supervision. At the same time, we will ensure the free flow of factors such as labor and capital in the market and promote market-oriented allocation of factors. For regions with overcapacity or high resource occupancy, they should actively explore how to use the development of digital economy to improve regional resource allocation and maximize resource allocation efficiency. More developed regions in the Yangtze River Delta should gradually tilt resources towards less developed regions to improve the efficiency of developed regions. The current situation is the overcapacity of regional resources and the insufficient allocation of resources in underdeveloped areas.

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