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How the Digital Economy Affects Urban Green Total Factor Productivity: Empirical Evidence from the Huaihe River Ecological Economic Belt

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Abstract: In the new normal economic development environment, the digital economy, as an emerging driving force, plays a key role in the promotion of the green economy. This paper takes the cities of the Huaihe River Ecological Economic Belt from 2007 to 2022 as the research object, and analyzes the mechanism of the digital economy on urban green total factor productivity based on the two-way fixed effect model. The study shows that the digital economy significantly promotes the green total factor productivity of cities in the Huaihe River Ecological Economic Belt by improving green technology innovation and optimizing the investment structure, and the effect is uneven in the east and low in the east and low in the west (negative in the west).

Keywords: Digital Economy; Green Total Factor Productivity; Huaihe River Ecological Economic Belt.

1. Introduction

As a core element of high-quality development, sustainable evolution is a key strategic deployment aimed at deepening the ecological transformation of growth mode and building a modern pattern with Chinese characteristics that coexists with humanity and nature. The digital economy is a new economic model that relies on an extensive and modern information network as the support platform and uses information and communication technology to analyze and integrate data resources is a key force to promote the optimization of economic structure. For example, in terms of technology, artificial intelligence and blockchain, as well as new retail models and new manufacturing methods in the field of application practice, constitute typical examples of the digital economy promoting productivity progress. As a leader in building regional competitive advantages in the information age, the development of the digital economy has become a key driving force for the economy to move towards a high-quality stage. The report of the 20th National Congress of the Communist Party of China anchors high-quality development as the core strategic basis for the construction of a modern socialist power, and emphasizes the urgency and importance of green and low-carbon economic and social transformation. The digital economy, as a result of the new technological revolution, can not only weaken the barriers to information flow between regions, accelerate the circulation of resource elements, and promote the coordinated development of regions, but also greatly improve the utilization rate of resource elements and more effectively promote the goal of green development The "14th Five-Year Plan for the Development of the Digital Economy" emphasizes that it is necessary to vigorously promote the deep integration between the digital economy and the real economy, guide traditional industries towards the path of digital and intelligent upgrading, and accelerate the deployment and application of the Internet of Things, big data, and artificial intelligence technologies deep integration with the green innovation and low-carbon development industry affirms the role of the digital economy in the process of urban green development.

The Huaihe River ecological and economic basin faces problems such as economic lag, insufficient infrastructure and low resource efficiency, but as a potential area in the central and eastern regions, it is crucial to national development. To this end, through regional cooperation meetings (such as the first joint meeting in 2019 and the fifth mayors' meeting in 2024) and local action plans (such as the 2024 Huaishang District Plan), we will promote the integration of scientific and technological innovation and ecological governance, achieve the goals of pollution prevention and control improvement and industrial upgrading in 2025, and build a green, livable and vibrant ecological economy in an all-round way by 2035. Therefore, exploring the factors of the digital economy in each city in the Huaihe River Ecological Economic Belt on the comprehensive green production efficiency of the city, and clarifying the internal logical relationship between the two, will help improve the level of digital economy and green development in the Huaihe River BasinThe promotion of high-quality economic development nationwide is of great practical significance [1].

2. Literature Review

Scholars at home and abroad have conducted a lot of research on the development of digital economy and green innovation, but the research on the relationship between digital economy and urban total factor productivity is still in the preliminary exploration stage, which can be summarized from the following two aspects:

2.1. Green Total Factor Productivity

As an evaluation system that couples development efficiency, resource use efficiency and ecological load, green total factor productivity plays a huge role in driving economic and social progress. At present, the research on green total factor productivity is mainly carried out from three levels: indicator construction, influencing factors and improvement paths.

First, for the measurement of green total factor productivity, many scholars use data envelope analysis (DEA) to evaluate

from the dual dimensions of input and output. The input variable is defined as environmental protection investment, and the degree of ecological environment optimization is taken as the output variable, and the ecological benefit model of environmental protection investment is constructed accordingly [2]. Some studies systematically integrate and propose an economic performance evaluation framework based on three aspects: economic growth, efficient resource allocation, and environmental protection [3]. Yang Long and Hu Xiaozhen used the entropy method to construct a comprehensive index of environmental pollution, and further combined with the DEA model to design green economy performance indicators [4]. In addition, some scholars have tried to cut in from a spatial perspective, providing new research ideas for constructing green benefit indicators [5].

Secondly, when exploring the driving factors of green total factor productivity, it can be mainly summarized into three levels: structure, system and technological innovation. Structural factors include the optimization of human capital structure [6] and the transformation and upgrading of industrial structure [7].Li Zihao and Mao Jun emphasized that the focus of improving green total factor productivity lies in the optimization of local government tax competition mechanism and the upgrading of industrial structure [8]. In terms of institutional factors, it involves the implementation of environmental regulations[9] and the market-oriented reform of foreign trade, Guo Aijun and Zhang Na pointed out that the institutional dividends released by the marketization process have a positive impact on promoting our country's green development performance[10]. For example, Wang Linhui believes that by reducing energy consumption and improving resource efficiency, the negative impact on the ecological environment can be significantly reduced as a whole, and then the improvement of green total factor productivity can be promoted [11]. In addition, the perspective of economic agglomeration [12] is another important perspective for analyzing the efficiency of green economy.

Finally, in terms of the improvement path of green total factor productivity, scholar Wang Qia constructed a dynamic panel vector autoregressive model of 78 economies around the world, and systematically deconstructed the impact of industrial niche transition and low carbon transformation of energy systems on green Nonlinear transmission mechanism of total factor productivity improvement [13]; Some studies are based on vertical fiscal imbalances [14]. and productive service industry agglomeration [15], economic growth goals [16], etc., to improve green total factor productivity. In addition, Yan Xiong has carried out corresponding research on the nonlinear effect of cultural and tourism integration on the comprehensive production efficiency of urban green production [17].

2.2. Digital Economy and Green Total Factor Productivity

As a highly integrated economic form, the role of the digital economy in guiding the development of the green economy cannot be ignored. Since the birth of the concept of digital economy, most of the research in the academic community has focused on the quantitative assessment of the digital economy, its influencing factors and its spatio-temporal evolution. Subsequent studies further clarified that rural revitalization, carbon emission control, enterprise innovation activities, and income distribution differences are closely related to the digital economy. In terms of the impact of the digital economy on green development, current research pays more and more attention to derivative industries related to the digital economy, such as the Internet industry, artificial intelligence technology, and big data [18-20] Integration and innovation model with other fields. These studies believe that the digital economy and its related industries can effectively achieve pollution control effects by improving factor and energy utilization efficiency, strengthening environmental supervision, and stimulating environmental investment enthusiasm. As the digital economy flourishes, its potential economic impact is gaining prominence. Some scholars have discussed the role of the digital economy in promoting the development of underdeveloped regions [21] and optimizing the labor force structure to improve employment quality [22], and the positive role shown in improving the natural ecological environment [23].

The discussion on the relationship between the digital economy and urban green total factor productivity mainly focuses on a single dimension, emphasizing that the digital economy can optimize the energy allocation structure and reduce carbon emissions by virtue of its advantages in digitalization, informatization, and platformization [24]. These findings further confirm the positive role of the digital economy in environmental protection. Other scholars have pointed out that the digital economy can empower the innovation of production and development processes and operation and management models [25], providing feasible paths and strategies for improving environmental quality. Regarding the specific implementation path of the digital economy to improve green total factor productivity, scholar Du Juan summarized four digital economy-driven green total factor productivity based on the combination of digital economy factors growth configuration [26]. In addition, more scholars are concerned about the impact of digital economy development on agriculture [27] tourism [28], Manufacturing [29] and other industries.

In summary, the marginal contribution of this paper is as follows: First, the existing literature mainly focuses on the deconstruction of the transmission path of digital technology industrialization to regional sustainable development transformation, while the dynamic coupling mechanism between the economic paradigm of digital technology and urban green total factor productivity has not yet formed a systematic research framework. Specifically, the existing literature pays more attention to the green spillover effect of digital industrial clusters from the perspective of new structural economics, but generally ignores the nonlinear interaction between digital factor endowment restructuring and green total factor productivity improvement. Secondly, most of the previous research perspectives stayed at the provincial level or only focused on individual large cities, and paid less attention to the cities of the Huaihe Ecological Economic Belt. Again, it is proposed to use the dual path of green technology innovation level and investment structure adjustment to indirectly enhance urban green total factor productivity, so as to enrich the connotation of existing research.

3. Theoretical Analysis and Research Hypotheses

Based on the strategic requirements of high-quality

economic development in our country, the digital economy is developing rapidly, and the digital economy empowerment acts on the green transformation of the traditional economy, affecting its production, transportation and sales, so as to achieve green development. The digital economy helps improve the green total factor productivity of cities, which is reflected in all aspects.

First of all, for the government, the rapid accuracy and real-time nature of the digital economy in disseminating information can alleviate the shortcomings of information asymmetry in the decision-making process. Using the information technology of related industries relying on the development of the digital economy, information about environmental pollution can also be transmitted to enterprises and consumers in a timely manner, which is conducive to the role of public supervision, so as to deal with pollutants that threaten the environment and urban green development in a timely manner, improve the green total factor productivity of the city, and ensure the green development of the city. Secondly, for enterprises, the digital economy can simulate various production links such as product production, transportation and consumption, improve the process and production process of enterprises, realize the digitalization, automation and intelligence of production, reduce the reuse rate of resources and reduce waste, so as to reduce the degree of pollution to the environment. Zhang Qiong et al. correlated carbon emissions with the performance of manufacturing enterprises and demonstrated the importance of green industrial development [30].

Finally, for consumers, the development of the digital economy can solve the problem of industrial chain fragmentation, such as online shopping and offline distribution and other services, solve the cross-time and space dissemination of products, and improve the efficiency of the supply chain. In addition, the digital economy has also developed home office, promoting the development of online medical care and education, and the increase in these industries not only solves some of the job needs, but also plays an important role in reducing energy consumption and environmental pollution, thereby improving the green development of cities. Based on this, hypothesis H1:

Hypothesis H1: The digital economy can help improve the green total factor productivity of cities.

The previous article focused on how the digital economy plays a role in urban green total factor productivity, and next, what are the transmission channels of the digital economy for affecting urban green total factor productivity? On the one hand, the digital economy helps to give birth to and develop a series of efficient and low-pollution digital industries, such as cloud computing, big data analysis, Internet of Things technology and artificial intelligence, etc., which provide technical support and power sources for the green development of cities, helping to improve cities green technology innovation capabilities; At the same time, in product production, logistics and transportation, and sales, the digital economy can improve enterprise processes and production processes, and help enterprises optimize their factor allocation and reduce single positions with digital, automated and intelligent goals energy consumption, increase resource availability, and enhance the green technology innovation of enterprises. On the other hand, although urban green development is strongly driven by investment structure adjustment, the development of digital economy may have a restrictive effect on the adjustment of regional investment structure. Although digital technology empowerment can strengthen the efficiency of enterprise information disclosure, it can reduce the structural contradiction of information asymmetry and the cost of entrustment-agent friction. However, it should be noted that the coupling mechanism between our country's digital economy and corporate governance is still in the process of cascade evolution and has not yet formed a systematic breakthrough pattern. In this process, the adjustment of industrial layout and investment structure may encounter challenges such as insufficient digital transformation capabilities, high transformation costs, and shortage of industrial digital talents, hindering the rapid integration of traditional industries and digital technology, and local governments may also face the problem of duplicate construction and excessive investment. In order to maintain existing income, enterprises tend to follow traditional production models and lack the motivation to open up new markets, which limits the role of the digital economy in promoting industrial structure upgrading and investment restructuring. This situation may become an obstacle, so that the development of the digital economy not only fails to promote the adjustment of regional investment structure, but inhibits its process, which in turn affects the improvement of regional green total factor productivity. Therefore, the following hypotheses are proposed:

Hypothesis H2: The digital economy can drive the growth of urban green total factor productivity by improving green technology innovation capabilities.

Hypothesis H3: The digital economy can promote the improvement of urban green total factor productivity by inhibiting investment restructuring.

4. Study Design

4.1. Variable Description

4.1.1. Interpreted Variables

Green Total Factor Productivity (GTFP). Referring to Wang Yafei's construction ideas, the evaluation of urban green total factor productivity in the Huaihe River Ecological Economic Belt. In this study, we draw on the super-efficiency SBM model proposed by Andersen et al. and integrate it with the undesired Malmquist productivity index method to construct the SBM Malmquist analysis method, which aims to accurately assess the quantitative relationship between resource input and benefit output [31-32] Specifically:

In terms of resource investment, we have selected two indicators: labor and capital. For labor input, we use the urban employment population at the end of the year as the measurement standard; Regarding the measurement of capital investment, this study adopts the perpetual inventory method advocated by Zhang Jun et al [33]. The calculation formula is as follows:

$$K_{it} = I_{it} + K_{it-1}(1 - \delta_{it}) \quad (1)$$

Here, K represents the accumulated stock of physical capital, I represents the total amount of capital formed in the year, and δ symbolizes the depreciation rate of capital.

For the evaluation of benefit output, we define two dimensions of indicators: expected output and unexpected output. For the expected output, we use the Gross Domestic Product (GDP) as the measure. For unexpected outputs, we consider the total amount of "three wastes" emitted by each region, including wastewater, sulphur dioxide, and dust and haze, which are used as key indicators for evaluation. Based on the above methods, the green total factor productivity of

cities in the Huaihe River Ecological Economic Belt from 2007 to 2022 was calculated. The detailed index System construction is shown in Table 1.

4.1.2. Core Explanatory Variables

Digital Economy (DIG). In the study of Liu Jun et al., they constructed a digital economy index system covering various provinces, especially introducing digital transaction indicators, and taking Internet development as the core of evaluation [34]. Based on the availability of urban data in the Huaihe River Ecological Economic Belt, this study refers to the construction framework of Bai Peiwen and Yuli, and mainly discusses the development process of the Internet and the status of digital finance [35]. In terms of evaluating the development of the Internet, this study adopts the methodology of Huang Qunhui et al., specifically selecting network access penetration, labor factor allocation structure, factor productivity output, and movement terminal coverage, etc. [36]. In the research of digital finance, this study adopts the "China Digital Inclusive Finance Index" jointly developed by the Digital Finance Research Center of Peking University and Ant Group as the core evaluation system. To comprehensively evaluate the various factors associated with explanatory variables, principal component analysis was used in this study, and the detailed index system construction is shown in Table 1.

Table 1. Evaluation index system

First level indicators	Secondary indicators	Level 3 indicators	Level 4 indicators	Nature of the indicator
Green total factor production rate	Resource investment	Labor input	The number of people employed at the end of the year	+
		Capital investment	Physical capital stock	+
	Benefit output	Expected output	Gross Regional Product	+
		Non-expected output	Wastewater discharge	-
			Sulfur dioxide emissions	-
			Dust soot emissions	-
Digital economy	Internet development	Network access penetration	Internet population density	+
		Labor factor allocation structure	Human capital concentration in information and communication technology (ICT) professions	+
		Factor productivity output	Consumption intensity of individual telecommunications services	+
		Mobile coverage	Number of mobile terminal users per 100 people	+
	Digital finance	Digital finance development	Digital Financial Inclusion Index	+

4.1.3. Mediating Variables

The selected mediating variables are: Green technology innovation capacity (PAT): According the Intellectual Property Office, urban green technology innovation is measured by using the urban green innovation output intensity indexability; Investment restructuring (INVEST) is parameterized by constructing a dynamic accounting model of fixed asset investment as a proportion of GDP.

4.1.4. Control Variables

The population size (POP) the logarithmic form of the total registered population. International Direct investment (FDI) is based on the proportion of actual foreign investment in GDP, and its knowledge spillover effect and "pollution paradise" effect have a positive driving and non-negligible restrictive effect on urban green total factor productivity, respectively. Degree of financial development (DEPO): This indicator is displayed by measuring the proportion of the city's total financial deposits and loans to the gross domestic product (GDP); Environmental regulation (ENVR): characterized by the comprehensive treatment rate of general industrial solid waste; Urbanization level (urban): The proportion of urban employed population, i.e., the share of urban employed population in the total population, is used as the benchmark for evaluation.

4.2. Model Settings

Based on the theory of sustainable development, an empirical model of the impact of digital economy on the energy level of urban ecological total factor productivity in the Huaihe River Ecological Economic Belt is constructed.

$$GTFP_{it} = \alpha_0 + \alpha_1 dig_{it} + \alpha_j Control_{jit} + \gamma city + \gamma year + \varepsilon_{it} \quad (2)$$

In the empirical model, $GTFP_{it}$, the green total factor productivity is characterized dig_{it} Referring to the level of digital economy development, the regression coefficient α1 and its significance reflect the intensity of the positive impact of the digital economy, and i and t identify the city and year, respectively, covering $Control_{jit}$ multi-dimensional control variables. In addition, city-specific dummy variables γcity and time-specific dummy variables γyear are incorporated to implement control strategies for two-way fixed effects. ε_{it} represents the random error component. To explore the specific path of the role of the digital economy and test the rationality of the hypotheses H2 and H3, this study adopted the mediation effect test step proposed by Wen Zhonglin et al. in 2014 [37] Based on this, the corresponding regression model system is constructed:

$$Med_{it} = \beta_0 + \beta_1 dig_{it} + \beta_j Control_{jit} + \gamma city + \gamma year + \varepsilon_{it} \quad (3)$$

$$GTFP_{it} = \tau_0 + \tau_1 dig_{it} + \tau_2 Med_{it} + \tau_j Control_{jit} + \gamma city + \gamma year + \varepsilon_{it} \quad (4)$$

Among them, Medit it is the mediating variable, including the ability of green technology innovation and the adjustment of investment structure. Equations (2)-(4) together constitute a mediating effect model. When Equation (2) α1 is significant, the joint significance of Equation (3) β1 and Equation (4) τ2 needs to be verified simultaneously, and the double verification mechanism constitutes a necessary and sufficient condition for the digital economy to affect the urban green total factor productivity through the intermediary path.

4.3. Data Sources

Based on the urban panel data of the Huaihe River Ecological Economic Belt from 2007 to 2022, this paper considers that Suixian and Guangshui City in Suizhou City, Hubei Province are county-level administrative units, and Suizhou City is uniformly used as the observation object, and Suqian and Bozhou were officially established in 1996 and 2000 respectively. All the data used in this study are derived

from the statistical yearbooks of each city, and refer to the data published on official websites such as the National Economic Development Bulletin, the Environmental Statistics Yearbook, and the Industrial Economic Statistics Yearbook.

Table 2. Descriptive statistics for each variable

Variable	Variable name	Number of samples	average value	Standard error	minimum	maximum
Green total factor productivity	GTFP	390	1.0081	0.0300	0.9198	1.0777
Digital economy	dig	390	0.2212	0.6373	-0.8493	1.9490
Population size	pop	390	0.6414	0.5048	5.3683	7.1381
International direct investment	fdi	390	0.0204	0.0158	0.0024	0.0866
Financial development	depo	390	1.9423	0.5827	0.8990	6.9284
Environmental regulation	envr	390	91.5494	11.1299	40.07	122.15
Urbanization level	urban	390	6.4924	0.3555	5.3766	7.1463

5. Analysis of Empirical Results

5.1. Baseline Regression

According to Table 3, after considering the fixed effects of the city and time dimensions, column (1) shows the preliminary regression analysis results without introducing any control variables, while column (2) presents the baseline regression results after incorporating a series of control variables. Empirical analysis shows that the digital economy and urban green total factor productivity show a significant correlation between robustness under the benchmark regression framework, and its impact coefficient continues to be significant at the 10% statistical level. After the introduction of control variables, the growth of urban green total factor productivity is increasingly driven by the digital economy, which has played a significant role in promoting the improvement of urban green total factor productivity, which in turn confirms the validity of hypothesis H1. With the continuous development of digital economy, with its unique advanced means and essential characteristics, it promotes the intelligent and digital development of related digital industries such as the Internet, big data and artificial intelligence, effectively solves the problems of excessive consumption of scarce resources and industrial chain fragmentation in traditional industries, and empowers urban green development. This conclusion is similar to the conclusions of Liu Qiang and Du Linyuan based on panel data at the provincial level and the Yangtze River Economic Belt, respectively [38-39].

Table 3. Benchmark regression results of the digital economy on urban green total factor productivity

variable	(1)	(2)
dig	0.013*	0.014*
	(1.79)	(1.81)
pop	-	0.048**
	-	(2.28)
fdi	-	-0.186
	-	(-1.27)
depo	-	0.007
	-	(1.49)
envr	-	-0.000**
	-	(-2.02)
urban	-	-0.015
	-	(-0.42)
Constant	1.020***	0.837***
	(160.67)	(3.50)
City fixed	YES	YES
The year is fixed	YES	YES
N	390	390
R^2	0.052	0.087

Notes: * p<0.1, ** p<0.05, *** p<0.01; The value of t-is in parentheses. The same below

5.2. Robustness Test

To verify whether the driving effect of digital economy on green total factor productivity in cities in the Huaihe River Ecological Economic Belt is robust, the following robustness verification steps are carried out, and the results are shown in Table 4. Specifically, first, the explanatory variable lags one period. The two-stage least squares method (2SLS) is used to conduct regression analysis on the lagging digital economy development level to control for indigenousness. Among them, column (1) presents the following information, and the urban green total factor productivity is still positively and significantly affected by the digital economy. Second, replace the core explanatory variables. The proportion of science and technology expenditure was used to replace the original explanatory variable, and the parameter estimation results showed that they were basically close to the original results, and the empirical results were stable. Third, the cross-fixation effect of province and year is included. By constructing a provincial-year two-way fixed effect model and a benchmark analysis framework to control the impact of provincial policy timeliness differences on urban green development, column (3) shows that the estimated coefficient of the digital economy is still significantly positive, which further reiterates the previous conclusion. Fourth, adjust the sample. In order

to further exclude the influence of extreme value samples on the empirical analysis results, this paper excludes three cities, including Wutong County in Nanyang City, Suixian County in Suizhou City, and Dawu County in Xiaogan City, which include county-level administrative units, and estimates based on the remaining samples. Column (4) shows that the results are still stable after adjusting the sample range. Fifth, 2% bilateral tail retraction adjustment. Column (5) shows that the results are robust after processing the extreme values.

In summary, the driving effect of the digital economy on urban green total factor productivity has a strong robustness.

Table 4. Robustness test

variable	(1)	(2)	(3)	(4)	(5)
	One period late	Replace the core explanatory variable	Add interactive fixation effects	Adjust the sample	Bilateral tail retraction
dig	0.014*	0.450*	0.014*	0.024***	0.014*
	(1.74)	(1.88)	(1.89)	(2.98)	(1.91)
Constant	0.657**	0.744***	5.628***	1.437 ***	1.296***
	(2.58)	(3.01)	(3.50)	(5.59)	(5.00)
Control variables	YES	YES	YES	YES	YES
Bidirectional fixation effect	YES	YES	YES	YES	YES
N	364	390	390	345	390
R2	0.097	0.096	0.110	0.115	0.101

5.3. Endogenous Test

In the robustness test, we introduce a lagging phase one digital economy index strategy, which can partially alleviate the endogenous problem of model setting bias, but in view of the risk of missing potential variables and the persistence of two-way causal transmission paths, concerns about indigenousness have not been fully addressed.

Therefore, this study uses the instrumental variable method (2SLS) to enhance the reliability of benchmark regression, and takes the interaction term between the telephone penetration rate and the urban Internet penetration rate in 1984 as the instrumental variable of the digital economy. Among them, the Internet penetration rate is characterized by the ratio of the number of people using the Internet to the total population in each region.

Table 5 The estimation of instrumental variables shows that there is an endogenous problem in the benchmark model, and the Kleibergen-Paap test (LM statistic rejects the hypothesis of deficiency, Wald F-value 22.70% 3E16.38 cut-off) confirms the validity of instrumental variables, and the second stage regression shows that the digital economy maintains a significant positive impact on urban green total factor productivity, and the conclusion is stable.

Table 5. Endogenous test

variable	(1) The first stage: dig		(2) Stage 2: GTFP	
iv	0.0000***	0.0000***	-	-
	(4.87)	(4.76)	-	-
dig	-	-	0.0087*	0.0111*
	-	-	(1.72)	(1.89)
Control variables	NO	YES	NO	YES
Kleibergen-Paap rk LM statistic	8.247***	7.931***	-	-
Kleibergen-Paap rk Wald F statistic	23.760 [16.38]	22.70 [16.38]	-	-
N	390	390	390	390
R2	0.328	0.310	-0.042	-0.036

Note: Inside the brackets are the cut-off values for the Stock-Yogo test

5.4. Mechanism Test

The above analysis and deduction show that the digital economy has a non-secondary driving effect on the improvement of urban green total factor productivity. To further explore its mechanism, this paper estimates (3) and (4), and in view of the relatively clear and direct causal relationship between the mediating variable and the interpreted variable, green total factor productivity, we mainly focus on the analysis of explanatory variables. The specific results are shown in Table 6.

(1) Green technology innovation ability. The theoretical analysis of this paper points out that the digital economy has the ability to optimize the production process and process of enterprises, which can improve the allocation efficiency of various production factors such as labor, capital and technology, strengthen the synergy and cooperation between various factors, and reduce the financing barriers of green R&D and enhance the availability of financial resources by reducing the financing barriers of enterprises for green R&DThe dual path drives the improvement of green technology innovation, and the regression results of column (1) confirm the transmission effect. The explanatory variable the digital economy, has a significant positive impact on green technology innovation capabilities, and its coefficient is significantly positive, indicating that it exerts a complete mediating effect, and the digital economy has a scale effect by empowering green technology innovation and research and development, resulting in a systematic leap in the city's sustainable development level. This conclusion is similar to the conclusion reached by Cheng Guangbin et al. based on provincial panel data [40].

(2) Investment structure adjustment. Based on the theoretical analysis of this paper, with the continuous advancement of our country's digital economy, some challenges may be encountered in the process of digital transformation, such as insufficient transformation capabilities, high transformation costs, and shortage of talents in the field of industrial digitalization, which may hinder the rapid integration of traditional industries and digital

technology, and local governments will also emerge The phenomenon of duplicate construction and overinvestment has led to the limited role of the digital economy in investment restructuring, which may also be the reason why the development of the digital economy inhibits regional investment restructuring. The data in column (3) shows that the explanatory variable, digital economy, hasan aspect of adjusting the investment structure that inhibits the effect and exerts part of the mediating effect. Based on the analysis results of these two columns of data, we can conclude that investment restructuring exerts part of the mediating effect, although the digital economy inhibits investment restructuring. However, this investment restructuring has promoted. The improvement of urban green total factor productivity to a certain extent.

In summary, the digital economy promotes the growth of urban green total factor productivity by improving the dual driving effect of green technology innovation and inhibiting investment structure adjustment, and verifies the hypotheses H2 and H3.

Table 6. Mechanism analysis

	(1)	(2)	(3)	(4)
	Green technology innovation capabilities		Investment adjustments	
	pat	GTFP	invest	GTFP
dig	275.492***	0.010	-0.065**	0.016**
	(3.93)	(1.32)	(-2.55)	(2.09)
pat	-	0.000**	-	-
	-	(2.24)	-	-
invest	-	-	-	0.033**
	-	-	-	(2.10)
Control variables	YES	YES	YES	YES
Bidirectional fixation effect	YES	YES	YES	YES
N	390	390	390	390
R2	0.596	0.100	0.703	0.099

5.5. Heterogeneity Test

In the Huaihe River Eco-Economic Belt, the geographical differences of the coastal cities in the basin and their respective resource characteristics, industrial structure and development level are taken into account Significant regional differences were shown. Therefore, the Huai River Basin is divided into three regions: the eastern central and western regions for subsample regression, among which the eastern cities include some cities in Jiangsu and Shandong, the central region is mainly some cities in Anhui, and the western region includes some cities in Henan and Hubei, which is helpful to further investigate the impact intensity of digital economy development. The estimated results are shown in Table 7.

As shown in Table 7, when discussing the three major regions of the east, central and west, it is found that the spatial differentiation effect of digital economy on the energy level of urban ecological total factor productivity in the Huaihe River Ecological Economic Belt shows the characteristics of unbalanced distribution. Specifically, the eastern urban agglomeration has a significant improvement effect, and compared with the central and western cities, the eastern cities have shown more obvious advantages in green innovation capabilities. The region has prominent advantages in capital and talents, as well as convenient transportation and developed education, so regional green development benefits from the improvement of infrastructure and other factors. Among the cities in the Huaihe Ecological Economic Belt, Jiangsu and Shandong, as two important sectors of economic development, can promote the innovative development of the regional digital economy, cultivate high-tech enterprises in the digital economy, help the green transformation of the traditional economy, and empower green development with their unique geographical location and solid economic foundation.

Table 7. Heterogeneity analysis

	eastern		Central		westward	
	Shandong and Jiangsu		Anhui		Henan and Hubei	
	(1)	(2)	(3)	(4)	(5)	(6)
dig	0.041***	0.035***	0.000	0.004	-0.011	-0.007
	(3.38)	(2.80)	(0.02)	(0.19)	(-0.80)	(-0.51)
Constant	1.021***	2.201**	1.006***	1.523***	1.010***	0.477
	(117.24)	(2.44)	(54.03)	(4.63)	(83.02)	(0.59)
Control variables	NO	YES	NO	YES	NO	YES
Bidirectional fixation effect	YES	YES	YES	YES	YES	YES
N	150	150	105	105	135	135
R^2	0.142	0.177	0.087	0.308	0.134	0.223

The estimated coefficient of digital economy in the central region is positive, but it does not pass the significance level test, which reveals that the improvement effect of the eastern urban agglomeration is significant, which is significantly better than that of the central region. Because of the vast area of agricultural green space, the industrial structure of the cities in the central region is mostly high-water-consuming and high-polluting enterprises mainly based on agricultural product processing. The estimated coefficient of digital economy in western cities is negative, and the growth of digital economy has not played a positive role in promoting the improvement of urban green total factor productivity, but has shown a certain degree of hindrance. For example, cities such as Luohe, Pingdingshan, Zhumadian

and Xinyang in Henan Province mainly rely on resource-intensive industries for their industrial development, and their dependence on resources is relatively high, resulting in low regional resource utilization efficiency and insufficient level of green development.

6. Conclusion and Suggestions

Based on the urban panel data of the Huaihe River Eco-Economic Belt from 2007 to 2022, this study evaluates and measures the green total factor productivity of each city. The core findings are summarized as follows: In the Huaihe Ecological Economic Belt, the digital economy significantly promotes the green total factor productivity of cities in the Huaihe Ecological Economic Belt by improving green technology innovation and optimizing the investment structure, and the effect is unevenly distributed. The improvement effect of the eastern urban agglomeration is significant and significantly better than that of the central region, while the digital economy in the western region shows statistically significant reverse adjustment characteristics on the urban green total factor productivity. Based on the above conclusions, the policy recommendations of the article are as follows:

First, give full play to the role of the digital economy in the Huaihe River Basin in promoting the improvement of urban green total factor productivity. Government enterprises and other economic entities should make good use of the "Internet +" medium in the process of improving urban green total factor productivity, and government enterprises and other economic entities need to clearly define various characteristics including economic development level according to local resource endowments, so as to be more effective Effectively play the positive role of the digital economy in promoting the growth of green total factor productivity in cities.

Second, multiple paths, including green technology innovation capabilities and investment structure adjustment, forming a non-single mediating adjustment effect on the energy level of urban green total factor productivity. There is a mutually reinforcing causal relationship between the digital economy and the ability to innovate in green technology. Specifically, the enhancement of green technology innovation capabilities has played a positive role in driving the promotion of the digital economy, and the application of digital technology has optimized the efficiency of the transformation of green technology innovation achievements.

Innovation entities such as enterprises, governments, and universities should cultivate innovative thinking, strengthen connections and cooperation with scientific research institutions, and promote the improvement of green innovation. In addition, to promote the accelerated development of our country's digital economy, we should make full use of digital information platforms to activate the investment vitality of social capital and guide the flow of scattered social funds to enterprises with green R&D strength, so as to alleviate their investment restrictions and capital shortages. This move aims to optimize the investment structure and improve the investment efficiency of enterprises, so as to promote the upgrading of production equipment and improve green total factor productivity, so as to achieve the city's green and sustainable development goals.

Third, implement policies according to local conditions, and pay attention to regional green and coordinated development in view of the regional differences in the eastern, central and western parts of the Huai River Basin. The three regions in the east, central and western regions have different support for the digital industry due to geographical environment, location conditions, industrial structure foundation and economic development conditions. It is recommended that local governments take the lead in cooperating with local universities and outstanding enterprises to increase investment in the digital industry, focus on building a high-level green development circle, and expand the scope of radiation. As a bridge connecting the development of the eastern and western regions, the central region should accelerate the pace of digital economy development. For Huainan, Bengbu and other places with relatively backward green development, solve the problem of coordinated development between economic development and environmental governance, implement targeted governance and adapt measures to local conditions, accelerate the construction of regional digital economy development highlands, and become a bridge for the joint development of the East and the West. The western region can further strengthen the construction of Internet infrastructure, increase environmental governance and technological innovation, and promote the integrated development of digital technology with local basic industries and characteristic industries, to improve the process and production process of local energy-consuming enterprises and realize the production process Transform to digitalization, intelligence, and automation, reduce environmental pollution levels, reduce resource reuse and waste, and promote the improvement of urban green total factor productivity.

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