Frontiers in Business, Economics and Management
ISSN: 2766-824X | Vol. 24, No. 1, 2026

A Study on the Impact of the Digital Economy on Green Total Factor Productivity in the Pearl River Delta Region

Ying Sun, Shufen Cao, Ke Liu, Min Pang

School of Economics and Management, Southwest Petroleum University, Chengdu, 610500, China

Abstract: Against the strategic backdrop of the deep integration of the 'dual carbon' goals and high-quality development, investigating the impact of the digital economy in the Pearl River Delta region on green total factor productivity is a key approach to resolving the contradiction between regional economic growth and ecological and environmental constraints, and to exploring pathways for the green transition of urban agglomerations. Based on panel data from the Pearl River Delta urban agglomeration covering the period 2006–2022, this paper examines, from an urban agglomeration perspective, how the digital economy influences green total factor productivity. The findings reveal that: (1) the digital economy in the Pearl River Delta urban agglomeration has significantly boosted its green total factor productivity; (2) the upgrading of the industrial structure and the efficiency of resource allocation within the Pearl River Delta urban agglomeration play mediating roles, whilst environmental regulations can reinforce the promotional effect of the digital economy on green total factor productivity;(3) The driving effect of the digital economy on the green total factor productivity of cities in the Pearl River Delta region is more pronounced in first-tier cities than in non-first-tier cities; (4) The driving effect of the digital economy on the green total factor productivity of cities in the Pearl River Delta region exhibits heterogeneity depending on the intensity of environmental regulations. Finally, targeted recommendations are put forward based on the research findings.

Keywords: Digital economy; Green total factor productivity; Pearl River Delta; Efficiency of resource allocation.

1. Introduction

Green development is the core objective and a key component of China's high-quality development. In recent years, the state has successively introduced a series of policy measures to promote a comprehensive green transition of the economy and society. These include setting out strategic targets for carbon peaking and carbon neutrality, issuing guiding opinions on accelerating the comprehensive green transition of the economy and society, revising the Catalogue of Industries for Green and Low-Carbon Transition, and strengthening ecological and environmental zoning controls. Balancing development with resource and environmental considerations has thus become a major development issue. Green total factor productivity is a core indicator for measuring the degree of harmony between economic growth and resource and environmental factors; it is the key manifestation and pathway to realising green development in terms of efficiency. As a vital lever for the transition from old to new growth drivers in China's economy, the digital economy plays a prominent role in industrial upgrading, resource allocation and green development. Exploring the pathways through which it contributes to enhancing green total factor productivity holds significant practical importance for deepening the practice of green development and resolving the contradiction between ecological constraints and economic growth.

The Pearl River Delta is a pioneering region and core economic hub of China's reform and opening-up, characterised by a high degree of external orientation and a prominent role in opening up to the outside world; the success of its green transition is directly linked to the overall picture of the country's high-quality development. This paper takes the nine cities of the Pearl River Delta (in the narrow sense) as its research sample to empirically examine the impact of digital economic development on green total factor productivity. To mitigate the interference caused by lags in explanatory variables, differences in measurement methods and endogeneity issues, the study conducts multi-dimensional robustness tests using lag effects tests, alternative measures and the instrumental variables method. Concurrently, mediation analyses are carried out from the perspectives of industrial structure upgrading and resource allocation efficiency, whilst moderation analyses are conducted from the perspective of environmental regulation. Furthermore, heterogeneity analyses are performed based on levels of economic development and the intensity of environmental regulation. This study lays a solid theoretical foundation and provides practical guidance for optimising high-quality development policies in the Pearl River Delta, whilst also contributing Chinese experience to other regions worldwide as they explore pathways to green development.

2. Literature Review

2.1. Definition and Measurement of the Digital Economy

The concept of the digital economy can be traced back to the 1990s. Tapscott was the first to coin the term 'the digital economy era', defining the digital economy as a system in which socio-political and economic elements are intertwined; this system utilises a variety of tools to efficiently acquire, accurately process and rapidly transmit information [TAPSCOTT, 1996]. Since then, research into the digital economy by scholars worldwide has gradually deepened; however, a unified definition of the digital economy has yet to be established. Zhang Liangliang et al. point out that, as an emerging economic form, the digital economy takes digital

information as its core factor of production, relies on information technology for support, utilises modern information networks as its primary platform, and realises the supply of products or services through the application of digital technologies; it integrates elements from multiple levels, including technology, industry, and producers and consumers [Zhang Liangliang et al., 2018]. At present, the characteristics and measurement criteria of the digital economy are still evolving, and no universally applicable measurement standards have been established either domestically or internationally. Furthermore, qualitative analyses of the digital economy are prone to being influenced by subjective factors; by comparison, quantitative research offers greater objectivity. Liu Jun et al. focus on dimensions such as the process of informatisation, the penetration of the internet, and the conduct of digital transactions to carry out a systematic assessment and precise measurement of the level of digital economic development in China's provincial-level administrative regions [Liu Jun & Yang Yuanyun, 2020] . At the same time, some scholars have shifted their perspective to provide a comprehensive evaluation of cities' levels of digital development based on aspects such as the process of industrial digital transformation and the development trends of e-commerce.

2.2. Measurement of Green Total Factor Productivity and Its Determinants

Green total factor productivity, which builds upon total factor productivity by incorporating undesirable outputs such as energy consumption and environmental pollution into input-output models, has now become a core indicator for assessing the level of green development [Chen Chaofan, 2016]. Zhao Wei comprehensively assessed the level of green development in the Yangtze River Delta urban agglomeration from three dimensions: ecological, economic and social greening [Zhao Wei, 2023]; Yang Li et al. employed the SBM-DEA model to conduct a measurement and analysis of green development efficiency across 30 provincial-level administrative regions in China [Yang Li et al., 2020]; Li Tianzhi et al. utilised the super-SBM model to conduct a measurement and analysis of the green development status of urban agglomerations in the Yangtze River Economic Belt [Li Tianzhi & Han Yuangang, 2023]. Currently, research into the determinants of green total factor productivity primarily covers various aspects, including environmental regulation [Xia Jianhong et al., 2024], the fiscal decentralisation system [Zhang Jianwei, 2019], smart city development, and innovation dynamism [Zhan Yong & Li Shan, 2022].

Consequently, this paper employs the SBM-GML measurement method—which, building upon SBM-DEA and super-SBM, enables further exploration of the evolution of dynamic efficiency—to measure the green total factor productivity of the Pearl River Delta urban agglomeration.

2.3. Research on the Impact of the Digital Economy on Green Total Factor Productivity

Numerous scholars have argued that the rapid development of the digital economy can significantly drive growth in green total factor productivity. Following empirical research, Xiao Yuanfei et al. found that the development of the digital economy plays a positive role in enhancing regional green total factor productivity; they further concluded that, compared with the western regions, the eastern regions have achieved more significant results in realising the digital dividend [Xiao Yuanfei&Jiang Yao, 2021]. Zhu Xi'an et al., drawing on inter-provincial panel data, found that the development of the digital economy plays a significant role in boosting green total factor productivity, and that this conclusion remains valid after undergoing various robustness tests [Zhu Xi'an et al., 2022]; Guo Bingnan et al. proposed that the development of the digital economy, through industrial upgrading pathways and green technological innovation measures, can help improve environmental pollution conditions in the region and neighbouring cities [Guo Bingnan et al., 2022]; Zou Jing et al. found that the development of specific dimensions of the digital economy, such as industrial digitalisation and the digitalisation of industries, serves as a long-term driving force for enhancing green total factor productivity [Zou Jing et al., 2023].

In summary, whilst much of the existing literature focuses on the overall impact and mechanisms of the digital economy on green development, research into the role of resource allocation efficiency and environmental regulation in the relationship between the digital economy and green total factor productivity remains scarce. Mechanism analyses tend to be one-dimensional, and empirical exploration at the urban agglomeration level is also relatively limited. Existing research indicates that the Pearl River Delta leads the three major urban agglomerations in terms of the level of its digital economy, making it a representative case for study. Accordingly, building upon existing academic findings and drawing on panel data from cities in the Pearl River Delta, this paper examines the underlying logic by which the digital economy influences green total factor productivity, empirically tests its actual effects, and, on this basis, proposes targeted policy recommendations.

3. Mechanism Analysis and Research Hypotheses

3.1. The Direct Impact of the Digital Economy on Green Total Factor Productivity in Cities of the Pearl River Delta Region

The digital economy possesses characteristics such as 'flexibility and agility, deep penetration, continuous innovation and environmental friendliness'. Through disruptive innovation and mechanisms for optimising resource allocation, it reduces enterprises' excessive use of resources and energy, mitigates adverse impacts such as environmental pollution and ecological degradation, and thereby drives the growth of green total factor productivity [Hui Xianbo, 2021]. From a theoretical perspective, enterprises can utilise the digital economy to reduce operational costs, stimulate technological innovation, and reduce over-reliance on resources, thereby advancing the process of green development [Wang Kai, 2021]. Digital technology is the key driver for the green transformation of the digital economy; it not only optimises enterprises' production and operations as well as their supply chain systems, reduces operating costs and improves the market's innovation ecosystem, but also enables the deep integration of various factors of production, guides their concentration in high-end industries, drives the digital and green transformation of enterprises, and ultimately enhances green total factor productivity [Wang Jun & Luo Qian, 2023]. In summary, this paper proposes the first hypothesis:

Hypothesis 1: The development of the digital economy can significantly enhance urban green total factor productivity.

3.2. The Indirect Impact of The Digital Economy on Green Total Factor Productivity in Cities of The Pearl River Delta Region

The digital economy enhances green total factor productivity by promoting the upgrading of industrial structures. Firstly, it optimises the inter-sectoral allocation of production factors, driving the industrial system towards greater efficiency from both the supply and demand sides; secondly, it promotes the deep integration of digital technologies with traditional industries, thereby restructuring production and marketing models; thirdly, it facilitates the smooth flow of digital information to enable collaborative cycles within industrial chains, thereby reducing transaction and matching costs; and fourthly, it drives the development of clean, emerging industries, achieving steady growth in green total factor productivity by capitalising on the dividends of structural upgrading.

Hypothesis 2: The development of the digital economy promotes the improvement of urban green total factor productivity by facilitating the upgrading of the industrial structure.

The digital economy drives an increase in green total factor productivity by enhancing the efficiency of resource allocation. The data factor can replace energy-intensive traditional factors, break down market barriers and facilitate the reallocation of factors towards green and efficient sectors; digital technology alleviates information asymmetry, curbs resource wastage and enables precise matching of supply and demand across regions; digital platforms consolidate fragmented resources, reducing the rate of factor idleness; efficient allocation also attracts high-calibre talent and investment in green research and development, driving the low-carbon optimisation of production processes, thereby systematically enhancing efficiency and empowering green growth through these four pathways.

Hypothesis 3: The development of the digital economy promotes an increase in urban green total factor productivity by improving the efficiency of resource allocation.

3.3. The Impact of Environmental Regulations on the Digital Economy and Green Total Factor Productivity in Cities of the Pearl River Delta Region

Environmental regulation provides an institutional framework to empower the digital economy to drive green total factor productivity. On the one hand, it compels enterprises to increase investment in digital technologies, applying them to energy management and pollution control to precisely optimise production processes and reduce energy consumption and pollution; on the other hand, it promotes synergistic innovation between digital and green technologies through policies such as green subsidies and carbon trading. At the same time, differentiated regulation is implemented to accommodate the specific characteristics of different industries, whilst carbon taxes and emission caps are used to raise the cost of pollution, thereby compelling enterprises to undertake dynamic digital optimisation, ultimately fostering the balanced development of the economy and the environment.

Hypothesis 4: Environmental regulation can reinforce the positive impact of the digital economy on green total factor productivity.

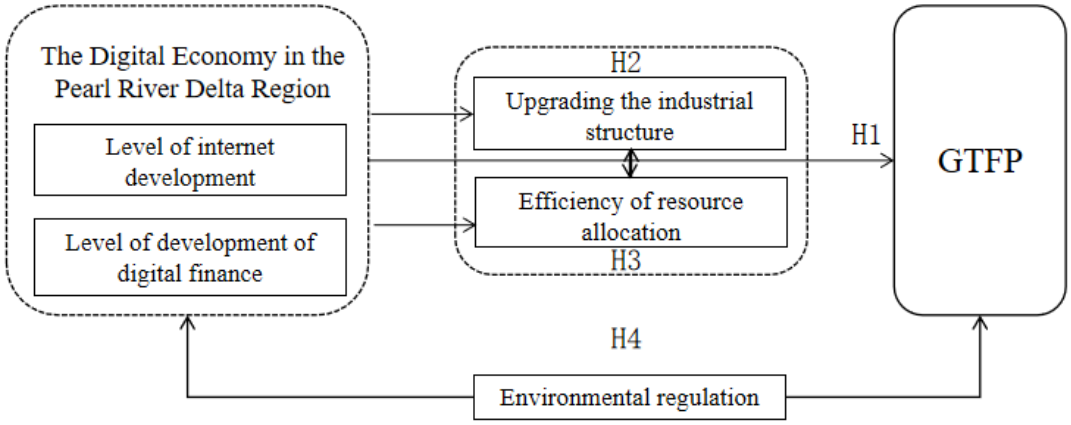


Figure 1. Schematic diagram of the theoretical mechanism

4. Empirical Design

4.1. Model Construction

4.1.1. Two-way fixed effects

To examine whether the level of digital economic development can enhance green total factor productivity, this paper constructs the following panel data model:

$$GTFPi,t = \alpha_0 + \alpha_1 DIG_{i,t} + \beta CV_{i,t} + \mu_t + \varepsilon_{i,t} \quad (1)$$

Where i and t denote prefecture-level cities and years, respectively; $GTFP_{i,t}$ represents the $GTFP$ for prefecture-level city i in year t; $DIG_{i,t}$ denotes the digital economy index for prefecture-level city i in year t; $CV_{i,t}$ represents a set of control variables; μ_t denotes the time fixed effect; α_0 denotes the constant term; and $\varepsilon_{i,t}$ denotes the random disturbance term.

4.1.2. Mediating Effects Model

Furthermore, based on the theoretical analysis presented above, the upgrading of a city's industrial structure and improvements in resource allocation efficiency can influence the effect of the digital economy on a city's green total factor productivity. Therefore, industrial structure upgrading and resource allocation efficiency are introduced as mediating variables to investigate the indirect effects of the digital economy on the green total factor productivity of cities in the Pearl River Delta region. The model is constructed as follows:

$$M_{i,t} = \gamma_0 + \gamma_1 DIG_{i,t} + \beta CV_{i,t} + \mu_t + \varepsilon_{i,t} \quad (2)$$

$$GTFP_{i,t} = \alpha_0 + \alpha_1 DIG_{i,t} + \alpha_2 M_{i,t} + \beta CV_{i,t} + \mu_t + \varepsilon_{i,t} \quad (3)$$

In this model, the level of digital economic development serves as the explanatory variable DIG, green total factor productivity as the dependent variable $GTFP$, and the upgrading of industrial structure and the efficiency of resource allocation as mediating variables M.

4.1.3. Moderation Effect Model

To test Hypothesis 4 proposed earlier, this paper builds upon Model (1) by introducing the interaction term $DIG_{i,t} \times ER_{i,t}$ between the variables 'digital economy' ($DIG_{i,t}$) and 'environmental regulation' ($ER_{i,t}$) to construct a model testing the moderating effect of environmental regulation, as shown in Equation (4).

$$GTFP_{i,t} = \alpha_0 + \alpha_1 DIG_{i,t} + \alpha_2 ER_{i,t} + \alpha_3 DIG_{i,t} \times ER_{i,t} + \beta CV_{i,t} + \mu_t + \varepsilon_{i,t} \quad (4)$$

4.2. Selection and Measurement of Variables

4.2.1. Core Explanatory Variables

Drawing on the measurement approach adopted by Zhao Tao regarding the level of the digital economy in Chinese cities, this paper constructs a measurement framework for the digital economy index of cities in the Pearl River Delta region from the dual dimensions of internet development and digital finance development [Zhao Tao et al., 2020]. To measure the level of internet development, indicators such as broadband penetration, mobile phone penetration, the development trends of telecommunications services, and the number of employees in internet-related industries were selected; whereas the level of digital finance development was characterised using the Digital Inclusive Finance Index published by Peking University [Xiao Yuanfei & Jiang Yao, 2021]. The measurement system is shown in Table 1 at. The standardised indicators were weighted using the entropy weighting method, and the digital economy indices for each prefecture-level city in the Pearl River Delta region for the period 2006–2022 were then calculated.

Table 1. Digital Economy Index Calculation Framework

First-level indicators	Second-level indicators	Tertiary Indicators	Data Notes
Digital Economy Index	Level of Internet Development	Broadband penetration rate	Number of broadband connections per 100 people
		Level of Telecommunications Service Development	Total volume of telecommunications services per capita
		Employment figures in internet-related industries	Proportion of employees in computer services and software
		Mobile phone penetration rate	Number of mobile phone subscribers per 100 people
	Level of digital finance development	Digital Inclusive Finance Index	Peking University Digital Inclusive Finance Index

4.2.2. Key Dependent Variable

This paper employs the SBM-GML model to measure green total factor productivity (GTFP) in nine prefecture-level cities in the Pearl River Delta region between 2006 and 2022. In terms of indicator selection, the number of employees per unit at year-end was used as a measure of labour input; capital stock as a measure of capital input; electricity consumption as a measure of energy input; real GDP as a measure of desired output; and industrial wastewater discharge, sulphur dioxide emissions, and smoke (dust) emissions as measures of undesired output. Given that the GML index calculated using this model reflects the year-on-year level of green total factor productivity development from year t-1 to year t, Consequently, following the research methodology of Cai Ling, this paper sets 2006 as the base year and assigns a value of 1 to the green total factor productivity for that year. Subsequently, the green total factor productivity index for each subsequent year is multiplied cumulatively by the base-year index to derive the green total factor productivity indices for each prefecture-level city in each year [Cai Ling & Wang Ping, 2022].

4.2.3. Mediating Variables

This paper identifies the degree of industrial structure upgrading and the efficiency of resource allocation as mediating variables. To measure the degree of industrial structure upgrading, drawing on the research of Gan Chunhui, the ratio of value added in the tertiary sector to that in the secondary sector is used as an indicator [Gan Chunhui et al., 2011]. In measuring resource allocation efficiency, following the research of Liu Cheng, we first calculate the degree of market distortion for each city and then compare this with the maximum degree of market distortion across all cities in that year; this ratio is used to represent resource allocation efficiency [Liu Cheng&Xia Jiechang, 2023].

4.2.4. Moderating Variables

Drawing on the research by Shao Shuai et al., the intensity of environmental regulation is measured by the proportion of the total number of characters in sentences containing environmental terms relative to the total number of characters in the government work report [Shao Shuai et.al., 2024].

4.2.5. Control Variables

This paper selects green technological innovation (patent), foreign direct investment (fdi), level of economic development (pgdp), urbanisation rate of the permanent resident population (urb), and government expenditure (govern) as control variables. Green technology innovation is represented by the logarithm of the total number of applications for green invention and utility patents in the given year plus one; the total amount of foreign capital actually utilised in the given year is used as an indicator of the region's degree of openness to the outside world; per capita gross domestic product is used to reflect the city's economic development status in the corresponding year; the ratio of the urban resident population to the total resident population is used to characterise the level of urbanisation of the resident population; and general public budget expenditure is used to represent government expenditure.

4.3. Data Sources and Sample Collection

Given that the 11th Five-Year Plan in 2006 first incorporated 'informatisation driving industrialisation' into national strategy, and that the Pearl River Delta serves as a

national pilot region for informatisation with a well-established and consistent statistical system covering the period 2006–2022—which meets the requirements for calculating green total factor productivity and constructing digital economy indicators—it is therefore reasonable to select raw data from the nine prefecture-level cities in the Pearl River Delta region for the period 2006–2022 to conduct this empirical study. Data sources are extensive, covering authoritative channels such as the *Guangdong Statistical Yearbook*, the *China Urban Statistical Yearbook*, the *Peking University Digital Inclusive Finance Index (2006–2022)*, the China Regional Economic Database, the China National Intellectual Property Administration, the Guangdong Provincial Department of Commerce, and the Guangdong Provincial Bureau of Statistics. With regard to missing data, this paper has applied smoothing techniques based on the underlying trends in the data.

5. Empirical Analysis

5.1. Descriptive Statistics of Variables

As shown in Table 2 at, the values for urban green total factor productivity (GTFP) range from [0.620, 3.546], with a median of 1.219, which is lower than the mean of 1.345. This indicates that the green total factor productivity of most cities is below the average level, and that there are differences in total factor productivity between different cities. The minimum and maximum values for the digital economy (DIG) are –0.286 and 4.224 respectively, indicating an imbalance in the level of digital economic development across different cities. Similarly, significant disparities can be observed in terms of green technology levels, the urbanisation rate of the resident population, and the efficiency of resource allocation.

Table 2. Descriptive Statistics Table for Variables

Variable Type	Variable	Sample Size	Mean	Standard error	Median	Minimum	Maximum
Dependent variable	GTFP	153	1.345	0.463	1.219	0.620	3.546
Key explanatory variables	DIG	153	1.050	0.993	0.978	-0.286	4.224
Mediating variable	TS	153	1.034	0.472	0.907	0.491	2.753
	ERA	153	0.574	0.194	0.530	0.243	1
Control variables	ER	153	0.867	0.533	0.824	0.342	7
Control variable	Lnpatent	153	6.558	1.694	6.624	2.197	9.975
	Lnfdi	153	12.04	0.841	11.846	9.806	13.76
	LnPGDP	153	11.27	0.578	11.298	9.546	13.06
	urb	153	79.28	17.26	86.39	39.75	100
	Lngovern	153	15.30	1.051	6.624	13.10	17.73

5.2. Analysis of Baseline Regression Results

A panel regression analysis was conducted to examine the impact of the digital economy on green total factor productivity in cities within the Pearl River Delta region. The results of the baseline regression are shown in Table 3 at. Regardless of whether fixed effects and control variables were included, the digital economy exerted a positive influence on green total factor productivity, with all results being statistically significant at the 1% level. Therefore, Hypothesis 1 is confirmed: the development of the digital economy in cities within the Pearl River Delta region can significantly enhance urban green total factor productivity.

The results of the control variable regression in Column (3) show that the three categories of variables have markedly different effects on green total factor productivity in Pearl River Delta cities. Foreign direct investment is significantly positively correlated with green total factor productivity; foreign-invested enterprises generally adhere to higher environmental standards and possess more advanced technological capabilities. Their clean production processes and energy-saving management expertise benefit local enterprises through technological spillovers, whilst also driving growth in green R&D investment and facilitating the green upgrading of industries. The urbanisation rate of the permanent resident population exhibits a negative correlation at the 5 per cent level. Rapid urbanisation in the Pearl River Delta is encroaching on ecological space and undermining environmental carrying capacity; high population concentration is driving up the marginal costs of pollution control, whilst inadequate spatial planning also hinders the realisation of economies of scale in environmental governance. Fiscal expenditure shows a significant positive correlation with green total factor productivity; increased government financial support for environmental governance and the development of green technologies provides a stable financial foundation for the green transition of cities.

Table 3. Baseline Regression Results

Variable Symbols	(1) GTFP	(2) GTFP	(3) GTFP
DIG	0.264*** (5.670)	0.509*** (4.128)	0.335*** (2.841)
Lnpatent	—	—	-0.014 (-0.127)
Lnfdi	—	—	0.233*** (3.048)
Lnpgdp	—	—	-0.246 (-1.305)
urb	—	—	-0.033** (-2.553)
Lngovern	—	—	0.919*** (3.352)
_cons	1.068*** (18.805)	0.886*** (7.411)	-9.533** (-2.568)
N	153	153	153
R^2	0.184	0.314	0.482
Fixed time	No	Yes	Yes
Individual fixed	No	Yes	Yes

Note: ***, ** and * denote significance at the 1%, 5% and 10% levels respectively; figures in brackets represent standard errors; the same applies throughout.

5.3. Robustness Tests and Endogeneity Analysis

This paper conducts robustness tests in the following two aspects: (1) The level of digital economic development may influence changes in regional green total factor productivity; however, it is also possible that regions with higher green total factor productivity indices are more inclined to develop digital technologies, thereby promoting the improvement of the level of digital economic development. To address this issue, this paper draws on Zhu Xi'an's method and analyses the level of digital economic development lagged by one period (l.DIG). (2) Drawing on the methodology of Guo Qiuqiu, we re-estimate the digital economy using principal component analysis, denoting the variable as DIG2. We substitute the values of the core explanatory variables from the principal component analysis for the original core variable values and incorporate them into the model in accordance with the original empirical analysis methodology [Guo Qiuqiu&Ma Xiaoyu, 2022]. Given the endogeneity between the digital economy and green total factor productivity, this paper further introduces an instrumental variable iv, drawing on the research by Huang Qunhui et al. [Huang Qunhui et al., 2019], using the product of the historical data on the number of post offices in each prefecture-level city in 1984 and the number of internet users in the corresponding year as the instrumental variable for the digital economy.

As can be seen from the table, l.DIG and DIG2 pass the significance test for the dependent variable at the 1 per cent level; simultaneously, the estimated coefficients of the instrumental variables in the first-stage regression results are significant at the 1 per cent level, indicating that the instrumental variables selected in this paper satisfy the correlation assumption. The results of the second-stage regression show that the digital economy has a significant effect on green total factor productivity at the 1 per cent level. This result is consistent with the conclusions drawn earlier, confirming the robustness of the empirical findings in this paper.

Table 4. Robustness Tests

Variable	Explanatory variable, one period lagged		Explanatory variable: alternative measurement		Instrumental variables method	
	GTFP	GTFP	GTFP	GTFP	Phase One	Phase 2
DIG	—	—	—	—	—	1.056*** (0.226)
l.DIG	0.640*** (3.596)	0.420*** (6.209)	—	—	—	—
DIG_2	—	—	0.232*** (3.968)	0.151*** (2.713)	—	—
iv	—	—	—	—	0.018*** (0.003)	—
_cons	0.913*** (7.866)	-10.902* (-2.036)	1.398*** (9.076)	-9.110** (-2.455)	5.680* (3.083)	-10.229** (3.983)
Control variables	Uncontrolled	Controlled	Uncontrolled	Controlled	Controlled	Controlled
Fixed time	Yes	Yes	Yes	Yes	Yes	Yes
Fixed individual	Yes	Yes	Yes	Yes	Yes	Yes
N	144	144	153	153	153	153
R^2	0.318	0.479	0.307	0.480	—	0.638
F	—	—	—	—	29.46	29.46

5.4. Mechanism Testing

5.4.1. Mediating Effects

To verify whether the digital economy can indirectly drive improvements in urban green total factor productivity through the upgrading of industrial structure and the efficiency of resource allocation, this study constructed a mediation model to conduct regression tests. The results indicate that, with regard to the industrial structure upgrading dimension, the digital economy significantly promotes industrial structure upgrading at the 5 per cent significance level, and both factors exert a positive influence on green total factor productivity at the 10 per cent significance level; Upon inclusion of the mediating variable, the coefficient for the digital economy decreased, indicating that the upgrading of industrial structure plays a partial mediating role, thereby confirming Hypothesis 2. With regard to the resource allocation efficiency dimension, the digital economy exerts a positive influence on resource allocation efficiency at the 10 per cent significance level; after introducing the mediating variable, the direct effect of the digital economy is no longer significant, whilst resource allocation efficiency significantly promotes green total factor productivity at the 1 per cent significance level, demonstrating a complete mediating effect, thereby confirming Hypothesis 3.

Table 5. Mediating Effects

Variables	Upgrading of industrial structure		Resource Allocation Efficiency	
	TS	GTFP	ERA	GTFP
DIG	0.169** (2.82)	0.262* (2.20)	0.0830* (2.34)	0.176 (1.78)
TS	—	0.432* (2.47)	—	—
ERA	—	—	—	1.924*** (7.79)
_cons	5.137** (2.72)	-11.75** (-3.14)	-0.899 (-0.81)	-7.802* (-2.56)
Control variables	Control	Control	Control	Control
Fixed effects	Yes	Yes	Yes	Yes
N	153	153	153	153
R^2	0.6041	0.5074	0.4749	0.6554

5.4.2. Regulatory Effects

The incentives and penalties imposed by government environmental policies constitute exogenous pressures driving cities to pursue green technological innovation and achieve a green, low-carbon transition. The results in the table below indicate that environmental regulation plays a positive moderating role in the impact of the digital economy on green total factor productivity; Hypothesis 4 is thus confirmed. This suggests that when environmental regulations are tightened, the Pearl River Delta region faces exogenous pressures to comply with environmental regulations and reduce emissions and carbon intensity, thereby increasing the motivation for green and low-carbon transition. At such times, there is a greater need to engage in innovation activities that integrate green technology with digitalisation, and the enabling effect of the digital economy on green total factor productivity is also realised to a greater extent.

Table 6. Test of the Moderating Effect of Environmental Regulations

Variables	(1) GTFP	(2) GTFP
DIG	0.335*** (2.84)	0.328*** (2.80)
DIG×ER	—	0.158** (1.98)
_cons	-9.533** (-2.57)	-9.824*** (-2.66)
Control variables	Control	Control
Time-fixed	Yes	Yes
Fixed per individual	Yes	Yes
N	153	153
R^2	0.482	0.499

5.5. Test for Heterogeneity

5.5.1. Heterogeneity in Economic Development Levels

Based on multi-dimensional indicators covering economic output, industrial structure, innovation capacity and regional synergy, this paper classifies the nine cities in the Pearl River Delta into first-tier cities (Guangzhou, Shenzhen, Dongguan) and non-first-tier cities, and conducts a heterogeneity analysis.Table 7show that, regardless of whether control variables are included, the development of the digital economy in first-tier cities enhances the cities' green total factor productivity; whereas columns (3) and (4) indicate that the digital economy in non-first-tier cities does not have a significant effect on green total factor productivity. This may be because first-tier cities are ahead of non-first-tier cities in terms of both digital infrastructure and technology penetration rates. Furthermore, first-tier cities are home to over 70 per cent of the universities and research institutions in the Guangdong–Hong Kong–Macao Greater Bay Area, forming a collaborative innovation network linking industry, academia and research. Additionally, first-tier cities outperform non-first-tier cities in terms of industrial structure and the efficiency of resource allocation; they also benefit from policy advantages such as free trade zones and digital economy demonstration zones, whereas non-first-tier cities are constrained by their administrative tier, leading to delays in policy implementation.

Table 7. Analysis of Heterogeneity in Economic Development Levels

Variables	Tier-1 cities		Non-first-tier cities	
	(1) GTFP	(2) GTFP	(3) GTFP	(4) GTFP
DIG	0.602*** (3.716)	0.310* (1.830)	0.046 (0.369)	0.122 (1.567)
_cons	0.735*** (4.125)	-10.576 (-1.530)	1.006*** (12.423)	-12.389*** (-3.803)
Control effect	Uncontrolled	Control	Uncontrolled	Control
Fixed time	Yes	Yes	Yes	Yes
Fixed individual	Yes	Yes	Yes	Yes
N	108	108	68	68
R^2	0.352	0.515	0.417	0.810

5.5.2. Heterogeneity in the Intensity of Environmental Regulations

This paper conducts a heterogeneity analysis of the Pearl River Delta urban agglomeration based on the intensity of environmental regulation, with Dongguan, Zhuhai and Jiangmen exhibiting lower regulatory intensity, whilst the remaining cities have higher regulatory intensity.

The regression results in Table 8 show that, regardless of whether control variables are included, the digital economy significantly enhances urban green total factor productivity in the high-intensity regulation group; conversely, in the low-intensity regulation group, the digital economy exerts a significant inhibitory effect on green total factor productivity. The root cause of this difference lies in the differing orientations of digital technology application brought about by regulatory intensity. High regulatory intensity creates a clear mechanism of external pressure, driving enterprises to focus their investment in digital technologies on green innovation. Whilst meeting environmental compliance requirements, this approach enhances green total factor productivity through the efficient allocation of resources and the reduction of pollution. Under low regulatory intensity, however, enterprises lack the impetus for green transformation; digital technologies are predominantly used to expand production capacity and achieve short-term cost reductions. Coupled with a lack of incentives for green collaborative innovation, this actually exacerbates resource consumption and pollution emissions, ultimately stifling the growth of green total factor productivity.

Table 8. Analysis of Heterogeneity in Environmental Regulatory Intensity

Variables	Cities with High-Intensity Environmental Regulations		Cities with low-intensity environmental regulation	
	(1) GTFP	(2) GTFP	(3) GTFP	(4) GTFP
DIG	0.648*** (5.211)	0.400*** (3.113)	-0.753** (-2.072)	-0.535* (-1.784)
_cons	0.714*** (5.055)	-8.243* (-1.922)	0.841*** (3.927)	-24.543*** (-3.643)
Control effects	Uncontrolled	Control	Uncontrolled	Control
Fixed time	Yes	Yes	Yes	Yes
Fixed individual	Yes	Yes	Yes	Yes
N	102	102	51	51
R^2	0.531	0.643	0.311	0.731

6. Conclusions and Recommendations

Against the backdrop of the coordinated advancement of the 'Dual Carbon' goals and the 'Digital China' initiative, enhancing green total factor productivity has become a central issue for high-quality development in the Pearl River Delta; there is an urgent need to clarify the impact of the digital economy on green total factor productivity and the pathways through which this impact is exerted. Drawing on panel data from the Pearl River Delta covering the period 2006–2022, this paper empirically examines the mechanisms through which the digital economy influences green total factor productivity. The study finds that the digital economy can significantly promote the growth of green total factor productivity in cities across the Pearl River Delta; in terms of the transmission mechanism, the upgrading of industrial structure plays a partial mediating role, whilst the efficiency of resource allocation plays a full mediating role, and environmental regulations can reinforce the green promotional effects of the digital economy. At the level of heterogeneity, first-tier cities in the Pearl River Delta are able to reap more substantial dividends from digital green growth, and differences in the intensity of environmental regulations also lead to divergent effects of the digital economy on green total factor productivity across different cities.

Based on the findings of the above research, four policy recommendations are put forward. Firstly, in line with the 15th Five-Year Plan for Digital Economic Development, the coordinated planning of digital infrastructure in the Pearl River Delta should be strengthened. With the national computing power hubs in Guangzhou and Shenzhen at the core, promote the integration of digital infrastructure across metropolitan areas; improve the coverage of new types of infrastructure such as 5G-A and the Industrial Internet, whilst prioritising green manufacturing parks; guide leading enterprises in key industries to participate in the design of infrastructure applications; reduce the costs of green transition for enterprises; and consolidate the hardware foundation for the digital economy to empower the enhancement of green total factor productivity. Secondly, the intermediary role in advancing the upgrading of the industrial structure and improving the efficiency of resource allocation should be activated. Promote the deep integration of digital technology with manufacturing and the service sector; transform traditional energy-intensive industries and cultivate high-end service industries to unlock the green dividends of industrial upgrading; and establish a unified regional digital factor trading platform to guide the reallocation of production factors from energy-intensive sectors towards digital and low-carbon industries, thereby continuously optimising the efficiency of resource allocation. Thirdly, strengthen the synergy between environmental regulations and the digital economy. Introduce two types of policy coordination documents to incorporate the application of digital technologies into the assessment criteria for environmental protection subsidies and carbon quota allocation; establish a region-wide digital supervision platform to enable precise control over corporate energy consumption and emissions; and implement differentiated guidance based on variations in regulatory intensity across different cities to maximise the impact of green empowerment. Fourthly, implement targeted measures based on regional heterogeneity. Harness the radiating and driving role of Guangzhou and Shenzhen as dual leaders to establish a cross-city mechanism for digital-green synergy; for cities with strong manufacturing sectors and those with ecological advantages, respectively advance digital transformation at the production end and the digital integration of ecological industries, thereby steadily narrowing regional disparities in green development.

Acknowledgements

A General Project Supported by the Academic Research Special Fund for High-Level Research Teams under the Sichuan Provincial Philosophy and Social Sciences '14th Five-Year Plan' 2025 Program: Mechanisms and Pathways of 'Digital-Green' Synergy for Advancing Sichuan Province's New Energy System (SC25T057)

A 2026 Research Project of the Sichuan Public Administration Society: Institutional Mechanisms for Deep Integration of Scientific and Technological Innovation and Industrial Innovation in the Oil and Gas Industry

References

[1] Tapscott, D. (1996). The digital economy: Promise and peril in the age of networked intelligence. McGraw-Hill. https://doi.org/10.4324/9781315706756

[2] Zhang, L. L., Liu, X. F., & Chen, Z. (2018). Strategic considerations on the development of China's digital economy. Modern Management Science, (5), 88-90.

[3] Liu, J., Yang, Y. Y., & Zhang, S. F. (2020). A study on the measurement and driving factors of China's digital economy. Shanghai Economic Research, (6).

[4] Chen, C. F. (2016). China's green total factor productivity in industry and its determinants: An empirical study based on the ML productivity index and a dynamic panel model. Statistical Research, 33(3), 53-62.

[5] Zhao, W. (2023). Can two-way FDI coordination promote urban green development?-Empirical evidence from the Yangtze River Delta urban agglomeration. Journal of Nantong University (Social Sciences Edition), (5), 49-61.

[6] Yang, L., Cao, H. M., & Ding, R. Z. (2020). Local government tax competition, FDI and green development efficiency. Journal of Chongqing University of Technology (Social Sciences), (5), 24-33.

[7] Li, T. Z., & Han, Y. G. (2023). A study on the impact of FDI quality on green development efficiency from the perspective of environmental regulation: A case study of the three major urban agglomerations in the Yangtze River Economic Belt. International Economic and Trade Exploration, (2), 53-68.

[8] Xia, J. H., Liu, S., Ding, C. F., et al. (2024). Environmental regulation and green total factor productivity: A catalyst or a hindrance? Economic Issues, (4), 60-67.

[9] Zhang, J. W. (2019). The impact of fiscal decentralisation on green total factor productivity. Statistics and Decision-Making, 35(17), 170-172.

[10] Zhan, Y., & Li, S. (2022). Smart city development, entrepreneurial vitality and high-quality economic development: An analysis from the perspective of green total factor productivity. Financial and Economic Research, 48(1), 4-18.

[11] Xiao, Y. F., & Jiang, Y. (2021). The impact of the digital economy on regional green total factor productivity. Science, Technology and Industry, 21(12), 21-25.

[12] Zhu, X. A., & Ma, Y. G. (2022). A study on the impact of the digital economy on changes in green total factor productivity. Economic Issues, (1), 55-63.

[13] Guo, B. N., Wang, Y., & Zhang, H. (2022). Has the development of the digital economy improved urban air quality?-A quasi-natural experiment based on national-level comprehensive big data pilot zones. Journal of Guangdong University of Finance and Economics, 37(1), 58-74.

[14] Zou, J., Wang, Q., Yan, H. L., et al. (2023). How the digital economy affects green total factor productivity: Evidence from Chinese prefecture-level cities. Soft Science, 38(3), 1-16.

[15] Hui, X. B. (2021). Digital inclusive finance and urban green total factor productivity: Underlying mechanisms and empirical evidence. Southern Finance, (5), 20-31.

[16] Wang, K. (2021). The digital economy, resource allocation and the optimisation and upgrading of industrial structure. Finance and Economy, (4), 57-65.

[17] Wang, J., & Luo, Q. (2023). The internal mechanisms and spatial spillover effects of the digital economy on common prosperity. Forum on Statistics and Information, 38(1), 16-27.

[18] Zhao, T., Zhang, Z., & Liang, S. K. (2020). The digital economy, entrepreneurial activity and high-quality development: Empirical evidence from Chinese cities. Management World, (10).

[19] Cai, L., & Wang, P. (2022). The digital economy and urban green total factor productivity: Impact mechanisms and empirical evidence. Statistics and Decision-Making, 38(9), 11-16.

[20] Gan, C. H., Zheng, R. G., & Yu, D. F. (2011). The impact of China's industrial structure transformation on economic growth and fluctuations. Economic Research Journal, 46(5), 4-16, 31. https://doi.org/10.12088/pku.1002-960X.2011.05.002

[21] Liu, C., & Xia, J. C. (2023). Online markets, digital platforms and resource allocation efficiency: The roles of price and data mechanisms. China Industrial Economics, (7), 84-102. https://doi.org/10.12081/pku.1006-480X.2023.07.005

[22] Shao, S., Ge, L. M., & Zhu, J. L. (2024). How can humans and nature coexist in harmony: Environmental regulation and environmental welfare performance from a geographical perspective. Management World, 40(8), 119-146. https://doi.org/10.19744/j.cnki.11-1235/f.2024.00100.

[23] Guo, Q. Q., & Ma, X. Y. (2022). A study on the impact of the digital economy on urban green total factor productivity. Modern Management Science, (5), 156-166.

[24] Huang, Q. H., Yu, Y. Z., & Zhang, S. L. (2019). Internet development and productivity growth in the manufacturing sector: Underlying mechanisms and the Chinese experience. Chinese Industrial Economics, (8), 5-23. https://doi.org/10.12081/pku.1006-480X.2019.08.001