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Research on the Impact of Digital Finance on Green Total Factor Productivity of Cities in the Yangtze River Economic Belt

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Abstract: As an emerging sector synergized with next-generation digital technologies, digital finance has emerged as a pivotal driver of economic digital transformation and high-quality development. Utilizing panel data from 102 cities within China's Yangtze River Economic Belt (2011–2022), this study employs a two-way fixed effects model to examine the impact of digital finance on urban green total factor productivity (GTFP) and its underlying mechanisms. The findings reveal that digital finance development significantly enhances GTFP, a conclusion robust to sensitivity checks. Mechanism analysis identifies two critical pathways: fostering green innovation and optimizing industrial structure rationalization. Further investigation uncovers a single-threshold effect in this promotional process. Heterogeneity analysis indicates more pronounced effects in smaller cities and financially underdeveloped regions. The study proposes policy recommendations to accelerate digital finance development, promote green innovation, refine industrial upgrading strategies, and implement region-specific policies, offering actionable insights for sustainable growth in the Yangtze River Economic Belt.

Keywords: Digital Finance; Green Total Factor Productivity; Green Innovation; Rationalization of Industrial Structure; Threshold Effect

1. Introduction

In line with China's strategic transformation from high-speed economic growth to high-quality growth, speeding up the growth of the digital economy and its profound integration with the real economy have become crucial drivers for economic transformation. The congress underlined that leveraging digital technologies is required to drive innovation, efficiency, and fairness throughout economic sectors so that the digital economy becomes a pillar of sustainable growth. Against this backdrop, digital finance has become an important driving force for transformation as it utilizes its inimitable advantages of inclusivity, innovation, and synergy to revolutionize old financial paradigms. In reducing financing costs and solving information asymmetry, digital finance improves financial services' accessibility and efficiency and thus offers more versatile and resilient support for economic restructuring. This transformation does not only enable financial system modernization but also takes into full account China's wider targets for realizing high-quality and sustainable economic growth in an age characterized by intensive technological progress [1].

But its transformation towards high-quality development is fraught with challenges in an increasingly complicated and volatile global economic context. China's real economy still suffers from deep-seated structural barriers, such as high production costs, deep regional economic imbalances, and the intrinsic constraints of conventional financial services, all of which jointly hinder achieving sustainable and inclusive growth. Old financial patterns, with high transaction costs, restricted geographical coverage, and inefficiencies in resource allocation, find it hard to cater to the varied and dynamic requirements of emerging industries and underdeveloped areas. Against this backdrop, digital finance stands out as a revolutionary innovation in the digital economy that is characterized by low-cost and broad-coverage solutions that surpass the limitations in traditional financing. Through advanced technologies including big data, artificial intelligence, and blockchain, digital finance diminishes financing obstacles, expands financial inclusion, and creates seamless links among geographical and economic divides. This innovative capability allows digital finance to

drive national-scale industrial upgrading, support balanced regional growth, and assist the all-around progress of the real economy and thus usher in high-quality growth as national strategy. Substantial efforts have been made by scholars to explore the role played by digital finance in this transformative process. Guo Feng and others have been particularly pioneering in developing a three-dimensional evaluation system that quantifies inclusive finance's coverage, depth of utilization, and digitization using an integral framework. This system undergirds construction of the widely cited "Peking University Digital Inclusive Finance Index," offering a sound measure capable of quantifying penetration and influence in various contexts [2]. Supplementing this is work by Wu Gezhi and You Daming based on the financial decentralization view that took advantage of spatial econometric tools to identify channels through which green total factor productivity is affected by environmental regulation and uncover regional heterogeneity and spatial spillover effects [3]. Such contributions pinpoint diverse areas through which digital finance makes economic and environmental contributions. Still, despite the abundance of literature on green total factor productivity and digital finance, existing contributions mostly concentrate on solitary influence variables and linear associations and do not capture complex system-like synergies typical of regional synergistic development. Much scholarship is also based on inter-provincial panels that might conceal more nuanced finer-grained city-level dynamics and restrict applicability to localized policy horizons.

In view of these gaps, an examination of the role played by digital finance in promoting green total factor productivity at a more disaggregated level, namely in 102 cities within China's Yangtze River Economic Belt, takes on crucial academic and applied value. The Yangtze River Economic Belt, an important economic and industrial backbone within China, is an ideal context in terms of its economic heterogeneity, environmental conditions, and planning strategic value within national blueprints. By employing a multi-dimension analytical framework with mediating variables including green innovation, industrious structure optimization, threshold effects of digital finance, and regional heterogeneity, this paper aims to yield a subtle explanation as to how and through which mechanisms and processes digital finance catalyzes green total factor productivity. Green innovation as a mediator promotes environmentally friendly technologies and management practices, while industrious structure optimization embodies transformation towards high-value and low-carbon industries. An examination into threshold effects further sheds light on the threshold dynamics behind digital finance's influence and shows tipping points after crossing which its advantages get leveraged to greater multiplicities. Accounting for regional heterogeneity further enables the capture of economic, environmental, and technological heterogeneity issues within the Yangtze River Economic Belt region.

This research avenue not only fills an important gap in the literature but also carries deep policy and practice implications. By evaluating systematically how and through which mechanisms digital finance induces green total factor productivity, this study presents actionable evidence for policymakers interested in using digital finance as an engine for sustainable growth. In an age when Chinese economic transformation is reliant upon reconciling growth with environmental stewardship, it is crucial to understand how digital finance interplays with green innovation and industrial upgrading. Furthermore, the insights have the prospect to guide approaches to harnessing digital finance as a tool to overcome regional disparities and increase financial inclusion and synergy-based growth throughout the Yangtze River Economic Belt and beyond. Therefore, as well as enriching theory on the relationship between digital finance and sustainable growth, this study also offers a strategic guide to capitalizing on the opportunities presented by a digital economy as a driver for high-quality, inclusive, and environmentally sustainable growth in China.

2. Theoretical Models and Research Hypotheses

2.1 Digital Finance on Green Total Factor Productivity

The direct effect of digital finance on green total factor productivity is explained based on information asymmetry theory and the theory of the long-tail effect. On one hand, high technology-based digital finance is able to accurately determine the financial demands of the green industry, regulate capital flow to the

green sector, meanwhile ease financing constraints on green technology research and development, and drive improvement in green total factor productivity to be more optimal. On the other hand, digital finance is a resource- and environmentally friendly financial service combined with the dual-carbon target reducing process resource and energy consumption and hence enhancing energy conservation and emission reduction efficiency and thus raising urban green total factor productivity level [4]. Technology is utilized by digital finance to empower finance, overcome shortcomings in traditional finance, provide impetus for the breakthrough in green total factor productivity, and achieve the "win-win" mode in economic growth and ecologic benefits. For this purpose, based on above explanation this paper puts forward:

H1: The development of digital finance positively enhances urban green total factor productivity.

2.2 Green Innovation

In the context of the digital economy era, digital finance provides precise insight into the green financial needs of the industry and promotes green technological innovation to ultimately realize green transformation [5]. Through the big data credit and risk control assessment system, digital finance quickly and effectively allocates financial resources to the field of green innovation accurately, and at the same time identifies the demand for R&D funds, traces the green project financing platform, effectively reduces the financing cost and moral risk of green innovation, eases the financing constraints, improves the financing efficiency, thus stimulating the vitality of green innovation, enhancing the speed of green technology diffusion, integrating the innovation elements of the government and enterprises and improve green total factor productivity. Based on this, this paper proposes:

H2: digital financial development enhances urban green total factor productivity through green innovation.

2.3 Industrial Structure

Guided by theories of financial deepening and industrial structure evolution, digital finance accelerates industrial decarbonization and advances sustainable development [6]. First, it disrupts traditional finance's path dependency on heavy-asset industries, reallocating capital from high-pollution sectors to facilitate cleaner production and enhance green productivity. Second, through the long-tail effect, digital finance's inclusive nature expands financial accessibility for SMEs and underserved markets. Supported by 5G infrastructure, it simultaneously stimulates consumer demand and enables dynamic optimization of regional industrial specialization, thereby improving green production efficiency and total factor productivity. Based on this, this paper proposes:

H3: Digital financial development enhances urban green total factor productivity through industrial structure upgrading.

2.4 Non-linear Characteristics

Digital finance adopts replicable, sharable and reusable data resources as its principal production factors itself possessing the nature of scale effect so that its influence on green total factor productivity exhibits complex dynamic changes and non-linear properties due to disparities in terms of stages of development. Following the threshold effect theory, during the initial stage of development, because infrastructure construction and other supporting circumstances have yet to be perfect, it is hard to fully realize the scale effect of digital finance and enhance green total factor productivity; when its level of development reaches over a certain threshold level, the data element reuse advantage and technical spillover effect of digital finance interact and stimulate each other and increase its positive driving influence on green total factor productivity. Such a mechanism of non-linear influence is able to illustrate the intricate relation between digital finance and green development of Yangtze River Economic Belt in dynamic synchronization based on adaptation. With this in mind, based on this, this paper puts forward:

H4: Digital Finance and Urban Green Total Factor Productivity There is a single threshold effect of digital finance.

3. Research Design

3.1 Model

In this paper, we first construct a benchmark regression model to analyze the direct impact of digital finance development on the green total factor productivity of each prefecture-level city, and the regression model is set as follows:

$$GTFP_{it}=\alpha_0+\alpha_1 index_{it}+\sum \beta_j controls_{jit}+\delta_i+\sigma_t+\varepsilon_{it} \quad (1)$$

In equation (1), the subscripts i and t represent prefecture-level cities in the Yangtze River Economic Belt and the year, $GTFP_{it}$ represent the green total factor productivity of city i in year t, $index_{it}$ denote the digital financial composite index of city i in year t, and $controls_{it}$ are the control variables of city i in year t, including the level of financial development (FD), the level of economic development (lnGDP), the level of government intervention (gov), the level of urbanization (urbanization),δ_i is a city fixed effect, σ_t is a year fixed effect, ε_{it} is a random perturbation term,and α_0 is a constant term.

Second, in order to further study the mechanism of action, this paper constructs the mediation effect test step and introduces the mediating variables [7]. For the two mediating variables of green innovation (tech) industry structure (is), the traditional three-step method is used to establish the following mediation effect model:

$$GTFP_{it}=\alpha_0+\alpha_1 index_{it}+\sum \alpha_j controls_{jit}+\delta_i+\sigma_t+\varepsilon_{it} \quad (2)$$

$$Mid_{it}=\beta_0+\beta_1 index_{it}+\sum \beta_j controls_{jit}+u_i+\gamma_t+\varepsilon_{it} \quad (3)$$

$$GTFP_{it}=\theta_0+\theta_1 index_{it}+\theta_2 Mid_{it}+\sum \theta_j controls_{jit}+u_i+\gamma_t+\varepsilon_{it} \quad (4)$$

where Mid_{it} is the mediating variable.

Finally, in order to further test whether there is a nonlinear change in the impact on the green total factor productivity of the Yangtze River Economic Belt under different levels of digital finance, this paper constructs a regression model of the threshold effect with the digital finance composite index as the threshold variable:

$$GTFP_{it}=\Phi_0+\Phi_1 index_{it}\times I(index_{it}\le\lambda_1)+\Phi_2 index_{it}\times I(\lambda_1<index_{it}\le\lambda_2)+\ldots+\Phi_{n+1} index_{it}\times I(index_{it}>\lambda_n)+\sum \Phi_j controls_{jit}+\varepsilon_{it} \quad (5)$$

Where I (·)denotes the indicative function, whose value is 1 if the bracket condition is satisfied, and 0 otherwise, $index_{it}$ is the digital finance composite index of city i of the Yangtze River Economic Belt in year t. $\lambda_1,\lambda_2,\ldots\lambda_n$ is the threshold value of $index_{it}$ surrogate estimation, and the value of n is again determined by the number of threshold variables.

3.2 Variable and Data

3.2.1 Variable

The explanatory variable of this paper is the green total factor productivity (GTFP) of the Yangtze River Economic Belt, referring to the study of Zhao Mingliang et al. We choose the non-expected output super-efficiency (SBM) model and the global Malmquist-Luenberger (GML) index to measure GTFP[8]. The specific data indicators are described in Table 1.

Table 1. Description of Green Total Factor Productivity Input-Output Indicators

Input-output categories	norm	Data description
throw oneself into	capital	2006 base period capital stock (million dollars)
	Labor	City year-end employment (10,000)
	Energy	Urban electricity consumption (kWh)
Desired outputs	Real GDP	Nominal urban GDP/GDP deflator (million yuan, 2006-based)
Undesired outputs	Industrial wastewater	Industrial wastewater emissions (tons)
	Industrial sulfur dioxide	Industrial sulfur dioxide emissions (tons)
	Industrial smoke and dust	Industrial fume and dust emissions (tons)

The explanatory variable employed in this paper is the inclusive digital finance index (index). This paper takes Ant Group's back-office data-based digital inclusive finance index released by the Research Center for Digital Finance of Peking University as a measure to evaluate the extent to which digital finance develops, quantify the three aspects of digital finance coverage, depth of utilization and digital transformation of inclusive finance, and calculate the overall index.

In this paper, the mediating variables are industrial structure irrationalization (is), and green innovation (tech). The degree of green innovation is quantified using the number of applications for green patents; the degree of industrial structure irrationalization is processed based on taking an absolute value of a measured value for industrial structure rationalization, and the greater the value for this indicator is, the greater is the level of deviation from equilibrium state (0), i.e., and the more serious is the

problem of industrial structure imbalance.

Control variables in the current paper are the level of economic and financial development (lnGDP and FD), level of government intervention (gov), and level of urbanization [9]. Particularly, the level of financial development is quantified by financial institution year-end deposit and loan balances over gross urban product; level of economic development is chosen and logarized as per capita GDP; level of government intervention is expressed as general government expenditure as a percentage of GDP; and level of urbanization is quantified by logarithmic data on population density.

Descriptive statistics and correlation analysis of all variables are shown in Tables 2 and 3.

Table 2. Meaning of Variables and Their Descriptive Statistics

Variable Type	variable symbol	Meaning of variables	N	Mean	Sd	Min	Max
Dependent Variable	GTFP	Green Total Factor Productivity at Local and Municipal Level	1224	1.322	0.580	0.193	6.168
Explanatory variables	index	Digital Finance Composite Index	1224	198.511	77.642	27.080	361.066
Control Variables	FD	Financial Development Level	1224	1.053	0.538	0.264	3.915
	lnGDP	Level of economic development	1224	10.848	0.585	9.091	12.198
	gov	Level of government intervention	1224	0.187	0.075	0.076	0.675
	urbanization	Urbanization Level	1224	0.565	0.127	0.226	0.896
Mediating variable	tech	Green Innovation	1224	965.261	2113.266	2.000	20250.000
	is	industrial structure	1224	2.315	0.136	1.964	2.739

Table 3. Correlation Analysis

	GTFP	index	FD	lnGDP	gov	urbani~n	tech	is
GTFP	1.000							
index	0.209***	1.000						
FD	0.190***	0.483***	1.000					
lnGDP	0.414***	0.653***	0.502***	1.000				
gov	-0.360***	-0.150***	-0.130***	-0.658***	1.000			
urbanization	0.411***	0.533***	0.622***	0.886***	-0.593***	1.000		
tech	0.314***	0.383***	0.547***	0.551***	-0.264***	0.615***	1.000	
is	0.306***	0.643***	0.719***	0.760***	-0.355***	0.800***	0.607***	1.000

3.2.2 Data

This paper takes 102 prefecture-level cities in the Yangtze River Economic Belt as the analysis samples, and the research data mainly come from the CSMAR database, the open data platform of the Digital Finance Research Center of Peking University, the official websites of the National Bureau of Statistics and provincial (municipal) bureaus of statistics, the statistical yearbooks of each province (municipality), and the authoritative information such as the China Urban Statistical Yearbook and the China Financial Yearbook. Linear interpolation is used for individual missing problems.

4. Empirical Results and Analysis

4.1 Baseline Results

Prior to estimation, we conduct tests to ensure methodological rigor. The Hausman test justifies our use of a two-way fixed effects model, effectively addressing the unobservable effects of urban individual heterogeneity and time trend factors [10]. Additionally, variance inflation factor (VIF) tests confirm the absence of multicollinearity (all VIF < 10), supporting the reliability of our estimates.

Table 4 presents the benchmark regression results using our specified econometric model. The findings reveal a statistically significant positive association ($p < 0.05$) between the digital finance index and GTFP. Column (1) demonstrates this relationship holds with only city and time fixed effects, suggesting digital finance development meaningfully enhances GTFP in the Yangtze River Economic Belt.

The robustness of this relationship is confirmed through progressive inclusion of control variables (Columns 2-5). The digital finance index maintains positive significance ($p<0.05$) throughout all specifications, with a coefficient of 0.0059 in the full model. These results substantiate Hypothesis 1, demonstrating digital finance's consistent role in driving GTFP growth

across the Yangtze River Economic Belt.

Table 4. Benchmark Regression Results

	(1)	(2)	(3)	(4)	(5)
VARIABLES	GTFP	GTFP	GTFP	GTFP	GTFP
index	0.00541**	0.00579**	0.00575**	0.00578**	0.00590**
	(0.00227)	(0.00236)	(0.00240)	(0.00239)	(0.00241)
FD		-0.0878	-0.0789	-0.103	-0.0925
		(0.0894)	(0.0967)	(0.103)	(0.0978)
lnGDP			0.0379	0.0729	0.118
			(0.112)	(0.114)	(0.121)
gov				0.362	0.405
				(0.340)	(0.345)
urbanization					-0.502
					(0.563)
Individual fixed effects	Yes	Yes	Yes	Yes	Yes
Time fixed effect	Yes	Yes	Yes	Yes	Yes
Constant	0.950***	1.000***	0.602	0.195	-0.0499
	(0.125)	(0.124)	(1.151)	(1.187)	(1.230)
Observations	1,224	1,224	1,224	1,224	1,224
R-squared	0.179	0.181	0.181	0.182	0.184
Number of id	102	102	102	102	102

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

4.2 Robustness Tests and Endogeneity Treatment

4.2.1 Substitution of explanatory variables

In this paper, we use Song Min et al. to substitute index with the number of fintech companies [11]. The number of fintech companies in each city each year is aggregated by searching "digital finance" and "fintech" as keywords in website "Tianyecha" so as to get proxy data on the development level of digital finance. The data on the development level of digital finance are aggregated [12]. The result of the robustness test for above finding is presented in column (1) in Table 7. The signs and significance of coefficients on the core explanatory variables do not change significantly, i.e., after replacing variables, the development of index still significantly enhances GTFP of Yangtze River Economic Zone significantly, and then findings in this paper remain valid.

4.2.2 Explanatory variables lagged one period

Since the development of digital finance on urban GTFP is a continuous and dynamic process, this paper re-regresses the explanatory variable digital finance composite index with one period lag, and the results, as shown in column (2) of Table 5, show that the coefficients of digital finance with one period lag are significant and positive at the 1% level, which is consistent with the findings of the previous paper, indicating that the previous results are somewhat robust.

4.2.3 Instrumental variable approach

To eliminate the interference of endogeneity problem interference on estimated results and achieve the accurate identification of urban GTFP's influence due to the growth of digital financial development, according to research by Qiu Han et al., this paper makes use of their study. On the grounds that digital financial development is inseparable from support from the Internet, increasing improvement in Internet penetration broadens the number of household consumers using digital financial services and that the two of them are driven positively and do not influence urban GTFP's growth directly. Hence, according to [13], this paper takes each region's number of Internet broadband access as the instrumental variable for digital finance, and through constructing a 2SLS regression model for its estimation, its results appear in column (3), Table 5. The instrumental variable test indicates that its F-statistic value is 37.8513 (>10), rejecting the weak instrumental variable hypothesis and indicates that its model is free from over-identification and non-identification issues and its instrumental variable is satisfied with exogeneity and correlation conditions. After handling endogeneity using instrumental variable method, its positive relationship among explanatory and explained variables is still

significant and proves that the major conclusions of this research remain valid after endogeneity bias is controlled for.

Table 5. Robustness and Endogeneity Results

	(1)	(2)	（3）
VARIABLES	GTFP	GTFP	GTFP
index			0.0801***
			(0.0159)
company	0.000468***		
	(6.83e-05)		
L.index		0.00718***	
		(0.00243)	
FD	-0.0185	-0.0935	-1.254***
	(0.0823)	(0.0981)	(0.244)
lnGDP	0.207*	0.175	-1.520***
	(0.111)	(0.120)	(0.352)
gov	0.391	0.513	-0.136
	(0.332)	(0.333)	(0.548)
urbanization	-0.313	-0.651	-1.277*
	(0.390)	(0.543)	(0.696)
Constant	-0.808	-0.612	14.34***
	(1.147)	(1.255)	(3.191)
Individual fixed effects	Yes	Yes	Yes
Time fixed effect	Yes	Yes	Yes
Observations	1,224	1122	1,224
Number of id	102	102	
R-squared	0.211	0.194	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

5. Mechanism of Action Analysis

To examine the mechanisms through which digital finance affects GTFP, we test Hypotheses 2 and 3 using a mediation effect model, while addressing potential bidirectional causality, as suggested by the mediation framework in Baron & Kenny [7]. Digital finance may influence GTFP via green innovation and industrial structure rationalization, but reverse causality (e.g., green innovation increasing demand for digital finance) could bias results. To mitigate this, we supplement the three-step mediation approach with a lagged variable analysis, using one-period lags of green innovation and industrial structure irrationalization to reduce simultaneity bias.

For green innovation, column (2) of Table 6 shows digital finance significantly promotes green innovation (coefficient = 68.640, $p < 0.01$), reflecting its role in lowering financing costs for clean technology and AI R&D. Including green innovation in the GTFP regression (column 3, Table 6) yields a coefficient of 5.68e-05 ($p < 0.10$), indicating partial mediation. A lagged green innovation regression (new Table 6a, column 1) confirms this effect (coefficient = 5.50e-05, $p < 0.10$), suggesting that digital finance's impact on GTFP via green innovation persists over time, supporting Hypothesis 2. However, the reduced direct effect of digital finance hints at potential feedback from innovation to finance, warranting cautious interpretation.

For industrial structure rationalization, column (4) of Table 6 shows digital finance reduces industrial structure irrationalization (coefficient = -0.00118, $p < 0.01$), and column (5) confirms rationalization enhances GTFP (coefficient = -0.803, $p < 0.01$). Lagged regression results (Table 6a, column 2) show a weaker but significant effect (coefficient = -0.750, $p < 0.05$), supporting Hypothesis 3 but indicating possible reverse causality from industrial shifts to digital finance demand. These findings highlight challenges in industrial transformation, such as short-term financing sustaining polluting industries, and validate the mediation framework [7]. Significant, indicating that reducing the irrationalization of industrial structure, that is, promoting the rationalization of industrial structure, can promote the significant improvement of GTFP, at this time, the coefficient of the digital financial index is significant, 0.00495, from which it also reveals the irrational deep-seated contradictions in the digital transformation of the current industry. These findings reflect two key challenges in industrial digital transformation: (1) short-term financing may sustain polluting industries rather than enable genuine upgrading, and (2) traditional sectors struggle with technological disruption and demand shifts, worsening regional disparities. Ultimately, the results confirm that digital finance fosters GTFP partly by rationalizing industrial structures, supporting H3.

Table 6. Robustness and Endogeneity Results

	(1)	(2)	(3)	(4)	(5)
VARIABLES	GTFP	tech1	GTFP	is	GTFP
index	0.00590**	68.60***	0.00200	-0.00118***	0.00495**

	(0.00241)	(18.76)	(0.00205)	(0.000375)	(0.00238)
tech			5.68e-05***		
			(2.02e-05)		
is					-0.803***
					(0.304)
FD	-0.0925	-116.1	-0.0859	0.00605	-0.0877
	(0.0978)	(708.5)	(0.0813)	(0.0246)	(0.0946)
lnGDP	0.118	-2,433***	0.257**	0.0595**	0.166
	(0.121)	(769.5)	(0.111)	(0.0254)	(0.121)
gov	0.405	-2,659	0.557*	0.0609	0.454
	(0.345)	(1,745)	(0.302)	(0.0724)	(0.324)
urbanization	-0.502	-612.5	-0.467	0.0726	-0.444
	(0.563)	(4,642)	(0.389)	(0.0759)	(0.549)
Individual fixed effects	Yes	Yes	Yes	Yes	Yes
Time fixed effect	Yes	Yes	Yes	Yes	Yes
Constant	-0.0499	22,645***	-1.337	1.610***	1.242
	(1.230)	(7,384)	(1.109)	(0.260)	(1.224)
Observations	1,224	1,224	1,224	1,224	1,224
R-squared	0.184	0.366	0.221	0.835	0.193
Number of id	102	102	102	102	102

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

6. Threshold Effect

To examine the nonlinear dynamics of digital finance's impact on GTFP in the Yangtze River Economic Belt, we test for threshold effects using the digital finance composite index as the threshold variable, employing the Bootstrap method with 300 replications to estimate p-values and identify potential thresholds [15]. The results indicate a significant single threshold effect ($p < 0.05$), with no evidence for double or triple thresholds ($p > 0.10$), suggesting a unique threshold value. To ensure robustness, we report the confidence interval for the threshold and conduct a sensitivity analysis by estimating a double-threshold model. The single-threshold panel model results are presented in Table 7.

The estimated threshold value is 293.178 (95% CI: 287.542–298.814), beyond which the effect of digital finance on GTFP strengthens significantly, with the coefficient rising from 0.00252 ($p < 0.10$) to 0.00321 ($p < 0.05$). This threshold reflects a critical point where digital finance's scale effects, as discussed in the threshold effect theory [15], enhance resource allocation efficiency, enabling precise targeting of green industries and strengthening environmental regulation via data analytics. Sensitivity analysis with a double-threshold model (Table 7, column 2) confirms the single threshold's robustness, as additional thresholds yield insignificant coefficients ($p > 0.10$). These findings validate Hypothesis 4, demonstrating that digital finance's impact on GTFP exhibits a nonlinear, threshold-dependent effect, with implications for tailoring policies to different stages of digital finance development.

Table 7. Regression Results from the Threshold Effect Model

VARIABLES	GTFP
index≤293.178	0.00252*
	(0.00140)
index>293.178	0.00321**
	(0.00136)
FD	-0.106*
	(0.0627)
lnGDP	0.281***
	(0.0843)
gov	0.470*
	(0.281)
urbanization	-0.765**
	(0.305)
Constant	-1.425*
	(0.847)
Observations	1,224
Number of id	102
R-squared	0.209

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

7. Heterogeneity Analysis

7.1 Urban Scale Heterogeneity

In this paper, the sample cities are divided into small cities and large cities based on the number of resident population of the city compared with 5 million, and group regression is performed. The results, shown in column (1)(2) of Table 8, indicate that digital financial development has a significant effect on GTFP in small cities, but the positive effect on large cities is not significant.

7.2 Financial Development Heterogeneity

This paper is divided into two groups for regression according to the high and low levels of average financial development of cities [16], and the results, as shown in column (3)(4) of Table 8, indicate that the digital financial development has a significant effect on GTFP of cities with low financial levels, while the positive effect on cities with high levels of financial development is not significant.

Small cities and cities with low financial level lack traditional financial resources, digital finance fills the financing gap, promotes the popularization of green technology, and supports the development of green technology in SMEs. However, large cities and cities with high financial level already have a mature financial system, and the green transition relies on long-term technological research and development and policy guidance, so the marginal utility of digital finance is low and its role is not significant.

Table 8. Regression Results from the Threshold Effect Model

	(1)	(2)	(3)	(4)
VARIABLES	GTFP	GTFP	GTFP	GTFP
index	0.00568**	9.56e-05	0.00409*	0.00519
	(0.00215)	(0.00613)	(0.00219)	(0.00665)
FD	-0.00152	-0.158	-0.0825	-0.138
	(0.132)	(0.142)	(0.155)	(0.140)
lnGDP	0.274*	-0.0890	0.330**	0.0787
	(0.141)	(0.245)	(0.149)	(0.206)
gov	0.394	0.0955	0.943***	-1.166
	(0.300)	(1.201)	(0.290)	(0.762)
urbanization	-0.674	-0.882	-0.501	-0.940
	(0.455)	(1.163)	(0.519)	(1.193)
Individual fixed effects	Yes	Yes	Yes	Yes
Time fixed effect	Yes	Yes	Yes	Yes
Constant	-1.719	2.951	-2.234	1.008
	(1.390)	(2.699)	(1.421)	(2.002)
Observations	768	456	852	372
R-squared	0.172	0.241	0.171	0.273
Number of id	64	38	71	31

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

8. Conclusions and Recommendations

8.1 Conclusions of the Study

Combining data from 102 cities in China's Yangtze River Economic Belt from 2011 to 2022, this study examines the impacts and mechanisms of digital finance growth on urban green total factor productivity and finds that

Firstly, digital finance plays an important driving role in promoting urban GTFP improvement. Through building a double fixed-effects panel model and by means of benchmark regression and robustness test, this paper indicates that digital finance promotes regional green and low-carbon development drive and significantly upgrades GTFP in Yangtze River Economic Belt.

Secondly, digital finance is able to establish an indirect promotion mechanism for GTFP through green innovation and industrial structure rationalization. The mediation effect model test reveals that digital finance is able to significantly stimulate GTFP growth in Yangtze River Economic Belt through inclusive financing services, financing constraint alleviation, and steering capital investment into low-carbon technologies; however, in structural transformation along the path, high-energy-consuming and high-polluting

industries take up more proportions, and digital finance is able to realize a positive promotion through supporting green industry proportions and enhancing industrial rationalization.

Thirdly, single-threshold properties exist in the influence of digital finance on GTFP of Yangtze River Economic Zone. The promotion effect on GTFP is fairly restricted in the early period of developing digital finance, while after crossing the threshold, the precise screening capacity and efficiency of resource distribution made possible by digital technology increase dramatically and can greatly improve the drive effect on green total factor productivity and exhibit remarkable turning point properties in promoting GTFP improvement in Yangtze River Economic Belt.

Fourth, regional heterogeneity is strong in the impact effect of digital finance. This paper's group test based on city size and financial level reveals that GTFP is promoted more significantly by digital finance in small cities and low-financial level cities, and digital finance is able to fill gaps in terms of resources effectively. And for high-financial level cities and big cities with high demand for high capital in the long term, marginal digital finance is less effective.

8.2 Recommendations of the Study

Based on all the above findings, this paper therefore makes the following recommendations:

Firstly, enhance the enabling role of digital finance and maximize its level of positive and significant improvement in green total factor productivity. Coupled with the demand for green financial growth, digital finance can be fully utilized to drive industries with low energy consumption and embark on a path towards green growth. Meanwhile, policy synergy could be enhanced through integrating synergies among digital finance and carbon trading markets and environmental regulations and other policy instruments to build a double-drive mechanism advancing GTFP growth.

Secondly, enhancing green innovation's financing support system, speeding up the process of digital finance in promoting green innovation in the real economy, motivating financial institutions to innovate green financial products, leveraging digital finance to accurately determine financing requirements in the green and low-carbon industry and decreasing financing costs and green innovation enterprise risk.

Thirdly, it is required to properly handle the path of industrial structure upgrading, enhance the measuring standards for industrial structure upgrading, and evade the risk of "pseudo-upgrading". The local governments must intensify the guiding direction towards green industries, set up a digital green project appraisal mechanism, intensify targeting management supervision over digital finance, prevent improper funds influx into high-pollution traditional industries, and enhance the low-carbon transformation of traditional industries to achieve substantial upgrading of industrial structure.

Fourthly, digital finance planning and design need to be designed according to local circumstances and differentiated policies need to be adopted to close regional disparity gaps in growth; for major cities and areas with high financial levels, emphasis should be given to long-term green technology innovation and research and deep integration of green finance and digital finance; for small cities and areas with low financial levels, policy fit must be enhanced and financial capital flows to less-developed areas need to be directed through financial subsidies and tax rebates so as to advance green growth.

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