

Article

Unlocking Green Growth: How Digital Finance Fosters Urban Sustainability via Innovation and Policy Synergy

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Abstract

The rapid advancement of digital finance profoundly impacts urban development by expanding and deepening financial services for the real economy, with significant ecological and economic implications. This study hypothesizes that digital finance significantly enhances urban green development by simultaneously promoting ecological and economic objectives. To test this hypothesis, we investigate the influence of digital finance on urban green development from theoretical and empirical perspectives. Utilizing panel data from 265 prefecture-level and above cities in China (2011–2023), we comprehensively analyze the impact, underlying mechanisms, and the moderating role of environmental policies. Empirical results confirm our main hypothesis: digital finance significantly enhances urban green development. Robustness checks, including variable substitution, difference-in-differences, and instrumental variable estimations, confirm the results' stability. Heterogeneity analysis reveals that the positive effect is more pronounced in peripheral cities (vs. core cities), central and western regions (vs. eastern region), and resource-based cities (vs. non-resource-based), highlighting digital finance's role in mitigating regional development imbalances. Mechanism analysis indicates that green technology innovation is the primary channel through which digital finance fosters green development. Furthermore, the beneficial impact of digital finance is significantly amplified in cities with stringent environmental regulations, underscoring the critical importance of well-designed environmental policy. Overall, the evidence robustly supports the hypothesis that digital finance promotes urban green development. This research provides robust empirical evidence and valuable policy insights for leveraging digital finance to advance sustainable urban development.

Keywords: digital finance; urban green development; green innovation; industry structure; environmental regulation



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1. Introduction

Effective Urban Green Development (UGD), balancing economic growth with ecological protection within densely populated and economically active urban centers [1], necessitates robust support from an efficient and high-quality financial system [2,3]. This imperative sits at the intersection of environmental economics, which emphasizes internalizing environmental externalities and valuing ecosystem services, and urban development theory, which grapples with the sustainable management of resource flows, infrastructure, and economic activity in complex spatial agglomerations. Recognizing this challenge, China's top-down design of its green finance policy framework has progressively improved, accelerating the financial sector's 'green transition' across regions. Financial innovation,

particularly in the form of dedicated green finance instruments, is thus a critical response to the market failures and financing gaps highlighted by environmental economics in the context of sustainable urban transformation.

However, practical implementation faces substantial hurdles rooted in the limitations of traditional finance. Its inherent characteristics—high collateral requirements and risk premiums—coupled with persistent information asymmetry concerning the environmental performance and risks of green projects, impede the effective integration of the financial sector's resource allocation function with its environmental responsibilities [4,5]. This often results in inefficient allocation of green financial resources, hindering UGD efforts. These barriers underscore the need for novel financial mechanisms capable of overcoming information gaps and reducing transaction costs, aligning with core goals within both financial innovation and environmental economics for sustainable urban development.

Digital Finance (DF), fundamentally characterized by the application of digital technologies (big data, AI, blockchain, IoT) to support financial transactions and decision-making, represents a significant evolution in financial innovation. Its defining features—dematerialization, digitization, convenience, and personalization—offer a potential solution to the limitations of traditional finance in accurately supporting the dual economic-ecological objectives of UGD. On one hand, DF empowers traditional financial institutions to overcome information barriers. By leveraging alternative data sources and advanced analytics, DF enables more accurate identification of genuine green enterprises and better matching with appropriate capital, enhancing the precision and inclusivity of green financial services [6]. This directly addresses information asymmetry concerns central to environmental economics and facilitates the financing of dispersed, small-scale green initiatives common in diverse urban landscapes. On the other hand, DF has catalyzed the emergence of entirely new financial models. Leading fintech firms like Ant Group and JD Digits have pioneered explorations in novel green financial products, streamlined green finance processes, and enhanced regulatory mechanisms. These emerging models complement traditional finance, collectively elevating the level of UGD [7]. This aspect highlights DF's role in driving systemic financial innovation tailored to sustainable urban development challenges.

Given its relatively recent emergence, academic research on DF requires further expansion and depth. Existing studies have predominantly focused on its direct economic benefits within the broader sphere of financial innovation, such as alleviating financing constraints [8], driving innovation [9], mitigating risks [10,11], and stimulating consumption [12,13]. In recent years, scholarly attention has gradually shifted towards the ecological implications of DF, primarily exploring two key areas relevant to environmental economics and urban development: Firstly, DF's role in empowering green development, such as enhancing the resource allocation efficiency of green finance for environmental protection [14], enabling green credit to foster green investments and growth [15], reducing innovation costs, improving financing efficiency for green innovators, and ultimately boosting the quality, efficiency, and service delivery of green finance towards sustainable outcomes [16]. Secondly, the multi-faceted effects of DF on urban energy conservation and emission reduction. Research indicates DF exhibits a significant energy-saving effect, improving urban energy and environmental performance notably through green technological innovation [6]. Simultaneously, DF demonstrates a substantial carbon reduction effect, effectively lowering urban carbon emissions [17]. Furthermore, DF plays a crucial role in broader urban emission reduction, contributing to decreased sulfur dioxide and wastewater discharges [7].

While existing research affirms DF's positive contributions to economic efficiency (a core concern of financial innovation) and specific ecological outcomes (central to environmental economics), significant gaps remain when viewed through the integrated lens

required for sustainable urban development. Most studies adopt a singular lens, focusing either on economic benefits or isolated ecological effects, lacking a holistic integration of these intrinsically intertwined dimensions within the UGD framework. Furthermore, the limited literature specifically examining DF's impact on the comprehensive concept of UGD—which inherently combines economic vitality, social well-being, and environmental quality in an urban context—often provides only surface-level empirical analysis, lacking deeper theoretical exploration of the underlying mechanisms or granular detail at the relevant spatial scale. A critical limitation, particularly for informing urban development policy, is the predominant reliance on provincial-level data, overlooking the critical heterogeneity, unique challenges, and policy levers present at the city level where UGD is implemented and experienced.

Addressing identified gaps at the intersection of financial innovation, environmental economics, and urban development, this study investigates the impact of Digital Finance (DF) on comprehensive Urban Green Development (UGD) in Chinese cities at or above the prefecture level. While acknowledging foundational work establishing DF's general positive link to environmental innovation and UGD (e.g., as confirmed in broader international studies and specific analyses within China), our research provides distinct contributions by delving deeper into the contextual nuances, mechanisms, and synergistic effects within the rapidly evolving Chinese urban landscape, thereby refining and extending the existing theoretical and empirical understanding:

(1) **Integrated Ecological-Economic Assessment Framework:** Moving beyond studies that often prioritize either ecological or economic metrics, this research explicitly integrates both dimensions into a comprehensive UGD evaluation. This approach critically assesses DF's capacity to foster simultaneous ecological conservation and economic growth within cities, addressing a key limitation in capturing the multifaceted nature of sustainable urban transitions—a challenge noted internationally but explored here with a specific, integrated metric tailored to the Chinese urban context.

(2) **Contextual Heterogeneity and Disparity Mitigation Potential:** Building upon the established recognition of DF's positive environmental impact, this study provides novel granularity by rigorously examining how this impact varies across distinct Chinese urban typologies defined by location (coastal/inland), administrative level (provincial capitals/ordinary prefectures), and resource dependency. This analysis goes beyond confirming a general effect to reveal DF's specific potential role in mitigating regional green development disparities within China. Such spatially explicit insights, particularly concerning the pronounced benefits for less developed central/western regions, peripheral cities, and resource-dependent cities, offer crucial, actionable guidance for crafting differentiated urban green policies in large, heterogeneous economies—a contribution highly relevant to addressing equitable development challenges common in emerging economies globally.

(3) **Empirical Validation and Refinement of Theoretical Pathways:** While prior literature, including international research, theorizes pathways like green innovation and structural change linking finance to sustainability, this study offers robust empirical validation of these specific mechanisms—green technology innovation and industrial structural upgrading—as the primary conduits through which DF drives UGD in the Chinese urban setting. Our rigorous mechanism analysis not only confirms the importance of these channels but also quantifies their relative significance within the specific institutional and economic context of Chinese cities, enhancing comprehension of the complex causal dynamics theorized in environmental economics and providing a concrete case study for comparative analysis.

(4) **Synergistic Role of Environmental Regulation:** A key distinctive contribution lies in empirically investigating the contingent nature of DF's impact. We demonstrate how

stringent environmental regulations significantly amplify DF's positive effect on UGD. This analysis of the regulatory-financial innovation nexus provides a crucial theoretical and empirical basis for understanding how policy interventions can actively shape and enhance the ecological outcomes of DF. It underscores the necessity of synergistic efforts between evolving financial innovations like DF and regulatory frameworks to achieve UGD objectives—a finding with significant implications for policy design in contexts seeking to leverage finance for sustainability, highlighting the critical role of regulatory quality alongside market innovation.

In summary, this study advances the literature by: (a) providing robust, context-specific empirical evidence on the integrated ecological-economic impact of DF within China's unique urban system; (b) uncovering nuanced heterogeneity linked to fundamental Chinese urban characteristics (location, admin level, resources), revealing DF's potential as a tool for reducing intra-national green disparities; (c) empirically validating and quantifying core theoretical mechanisms (green innovation, industrial upgrading) within this specific context; and (d) critically establishing the amplifying role of environmental regulation, demonstrating the need for policy-finance synergy. While confirming core relationships observed in broader international literature (e.g., DF's link to eco-innovation), these contributions offer granular insights into the functioning of these relationships within a major developing economy undergoing rapid digital and green transitions, thereby enriching the global understanding of how financial innovation interacts with local contexts and policy environments to shape sustainable urban outcomes.

2. Theoretical Analysis and Research Hypotheses

Financial systems are pivotal in shaping economic trajectories. Consequently, the transition from extensive growth to a green development model necessitates corresponding financial evolution. Digital Finance (DF), emerging from the convergence of internet technologies and financial services, derives its core value from leveraging digital innovations—such as big data analytics, artificial intelligence (AI), and cloud computing—to profoundly empower and expand the traditional functions of finance. This empowerment significantly enhances the efficiency and capacity of the financial system to service green development, manifesting in the creation of novel green finance models, the refinement of environmental risk assessment and management, and the amplification of finance's catalytic role in mobilizing societal resources to support Urban Green Development (UGD) [18–20]. Crucially, DF facilitates efficient data and information flows, optimizing financial resource allocation and reinforcing finance's position as a central hub in guiding socio-economic activities towards a green transition.

2.1. Theoretical Analysis of the Impact of Digital Finance on Green Development

As an integration of digital technology and finance, digital finance retains the fundamental attributes of finance despite being empowered by digital technologies. Therefore, literature on the relationship between finance and green development provides theoretical insights for this study (Figure 1). Most studies affirm the positive role of finance in promoting green development. At the macro level, financial development facilitates the optimization of resource allocation, leading to more rational and cleaner industrial and energy structures. At the micro level, financial development effectively reduces corporate energy consumption and pollution emissions [21–24]. Further research reveals that financial development significantly enhances green total factor productivity (GTFP). Consequently, digital finance, embodying the core attributes of finance, should similarly exert a positive effect on GTFP. Another key characteristic of digital finance is its empowerment through digital technologies. The deep application of these technologies provides new momentum

for green growth. Specifically, the green economic effects of digital finance manifest in the following aspects:

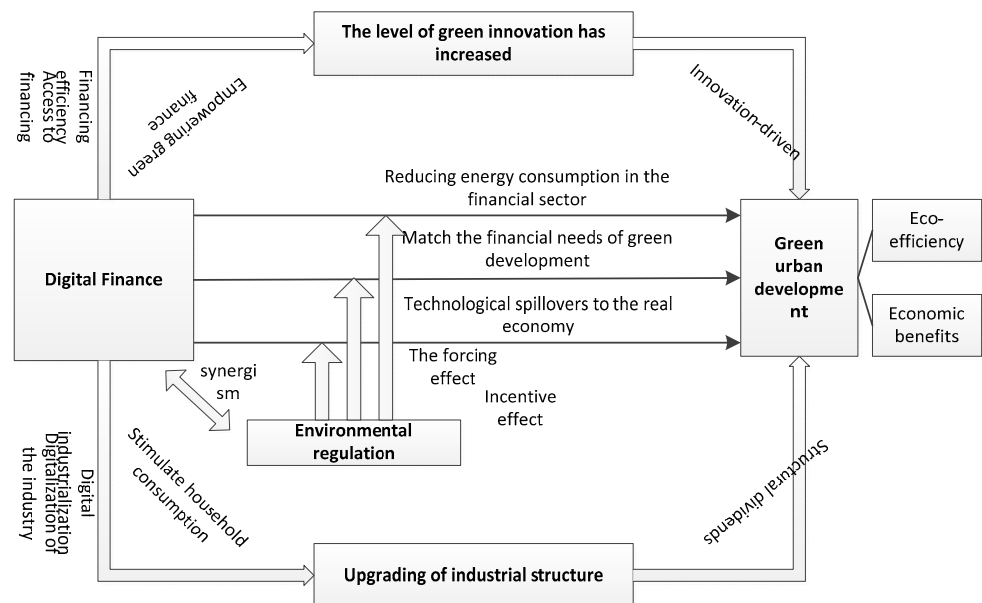


Figure 1. Theoretical framework.

Firstly, digital finance represents an environmentally friendly financial model. Compared to traditional finance, which primarily relies on manual services and physical branches, digital finance demonstrates green advantages of low cost, high efficiency, and low energy consumption: digitalized operations extend financial coverage and reduce transaction costs; mobile payments and settlements enrich the scope of finance and improve resource allocation efficiency; contactless transactions via internet platforms significantly reduce the resource consumption associated with traditional business processes [25,26].

Secondly, digital finance fosters novel green consumption patterns and lifestyles. Today, digital finance applications have become indispensable in modern life. Low-carbon consumption and lifestyle models—such as mobile ticketing, electronic invoicing, shared bikes, and carbon-reduction initiatives like Ant Forest—not only help reduce resource consumption and cultivate environmentally conscious consumers but also link individual environmental awareness to collective green actions [27,28]. This expands public participation in environmental protection, encourages deeper public engagement in conservation efforts, fosters a green living ethos, generates green economic benefits, and fosters a closer relationship between humanity and nature.

Thirdly, digital finance optimizes the allocation of green financial resources. The report to the 19th CPC National Congress proposed building green finance into a new engine for establishing an ecological civilization and a Beautiful China. Enhancing green growth through green finance has become a major direction for reforming China's financial system. However, the effective allocation of green financial resources heavily depends on a high degree of information symmetry between financial institutions and enterprises. Digital finance addresses this by comprehensively mining and gathering information, thereby expanding the information set and mitigating information asymmetry. Simultaneously, it enables precise matching between suppliers and demanders of green financial resources, enhancing allocation efficiency and enabling these resources to effectively contribute to green economic growth [29,30].

Finally, digital finance serves as a new green driving force. The next-generation digital technologies embedded within digital finance have achieved breakthroughs in

critical technologies. While accelerating the deep integration of finance and technology, it also drives the digital transformation and intelligent upgrading of traditional industries, thereby helping reduce resource consumption and pollution emissions. Thus, digital finance embodies a new green momentum, simultaneously supporting green development and accelerating technological innovation, ultimately contributing to the improvement of GTFP.

Based on the above analysis, digital finance can drive transformations in both green outcomes and efficiency. While reducing energy consumption and pollution, it also enhances resource allocation efficiency, ultimately promoting the growth of GTFP. It can be argued that the development of digital finance not only provides a new pathway for green growth on the financial supply side but also expands the space for green development, creating new growth poles. Accordingly, this paper proposes the following hypothesis:

Hypothesis 1. *Digital finance has a positive promoting effect on Green Development.*

2.2. The Mechanism by Which Digital Finance Influences Green Development

Further, this paper examines the potential channels through which digital finance influences green total factor productivity (GTFP). Currently, China's economy has entered a "three-phase superposition" new normal growth stage. Achieving high-quality green economic development against this backdrop necessitates breakthroughs in green technology innovation to overcome green growth constraints and fostering new development momentum through industrial structure transformation. The rapid development of digital finance provides a novel pathway for accelerating green technology innovation and promoting industrial upgrading.

Firstly, digital finance promotes green technology innovation. Compared to general technological innovation, green technology innovation is characterized by higher upfront investment costs, slower returns, greater uncertainty, and elevated risks. These factors weaken corporate incentives for pursuing green innovation. Particularly for highly innovative SMEs, financing constraints reinforce short-sighted behavior favoring production investment over green innovation. Digital finance injects new momentum into green technology innovation through several mechanisms [31]. Specifically, it extends the reach of traditional finance, enabling long-tail groups like micro and small enterprises—often excluded by traditional financial institutions—to access financial services, thereby providing a beneficial incremental supplement. Concurrently, it leverages "soft information" such as transaction records for credit assessment and loan issuance, lowering the credit barriers imposed by traditional finance's reliance on "hard information" like financial statements, thus optimizing the existing financial structure and freeing up more capital for technological innovation, including green innovation. Furthermore, digital finance diversifies data and information channels, reducing information asymmetry and enhancing corporate transparency. This facilitates stronger government pollution oversight, lowers public participation costs in environmental supervision, effectively curbs environmental corruption, and compels enterprises to increase green technology R&D to adapt to the digitized external environment. Additionally, it accelerates loan approval processes within financial institutions, minimizing human intervention and rent-seeking opportunities. This reduces institutional transaction costs for green technology innovation while fostering a more conducive external innovation environment. Finally, digital finance embodies the deep application of next-generation communication technologies in financial services; thus, its development inherently involves breakthrough innovations in critical digital technologies, which themselves constitute a form of green technology innovation. In summary, digital finance exerts a positive promoting effect on green technology innovation. Green

technology innovation, in turn, accelerates the replacement of outdated, energy-intensive technologies with advanced clean alternatives, reducing resource consumption and pollution emissions. Moreover, innovations in digital technology overcome spatial and temporal constraints on factor mobility, accelerate resource flows, and enhance real-time data mining, facilitating effective supply-demand matching and precise alignment. This guides rational resource allocation, reduces mismatches, improves economic operational efficiency, and ultimately promotes GTFP enhancement.

Secondly, digital finance drives industrial structure upgrading. Specifically, it breaks the limitations of physical branches, expanding financial service coverage. This enables cleaner, more environmentally friendly industries to access financial resources on par with high-energy-consumption, high-pollution priority or popular sectors, effectively alleviating capital distortion and financial misallocation, thereby reducing overcapacity and promoting industrial structure rationalization. Moreover, the widespread adoption of digital finance deepens the integration of digital technologies with industrial chains, accelerating the networking, intelligentization, and servitization of traditional industries [32–35], and injecting new momentum into their green transformation. Simultaneously, its vigorous development spurs the emergence of new digital and intelligent industries demanding higher technical skills and labor quality, attracting high-caliber talent and cutting-edge technologies towards these emerging sectors. This helps elevate the proportion of knowledge-intensive industries, propelling the industrial structure towards higher value-added segments and promoting industrial structure advancement [36–38]. Therefore, digital finance expands industrial space and extends industrial domains by promoting both industrial structure rationalization and advancement. As a converter of production factors into economic growth, industrial structure upgrading enhances resource utilization efficiency, improves environmental quality, strengthens factor synergies, optimizes resource allocation, releases structural dividends leading to efficiency and momentum transformation, and ultimately promotes GTFP enhancement.

Based on this analysis, the following hypotheses are proposed:

Hypothesis 2a. (*Green technology innovation effect*): Digital finance enhances green total factor productivity by promoting green technology innovation.

Hypothesis 2b. (*Industrial structure upgrading effect*): Digital finance enhances green total factor productivity by driving industrial structure upgrading.

2.3. Moderating Role: Environmental Regulation (ER)—The Institutional Condition for Financial Function Efficacy

The effective contribution of digital finance to green development requires synergistic support from complementary environmental regulation policies and relevant laws and regulations [39]. The Porter Hypothesis posits that appropriately designed environmental regulations by governmental bodies increase external pressure, compelling firms to pursue green technological innovation and reduce environmental pollution [40,41]. The validity and applicability of the Porter Hypothesis within the Chinese context have been empirically verified by relevant studies [42,43]. Green innovation and green development represent economic activities characterized by positive externalities. Achieving higher environmental benefits at the expense of corporate economic profits inherently conflicts with the “rational actor” paradigm of firms. Implementing environmental regulation policies addresses this by internalizing the environmental benefits through institutional arrangements, thereby correcting market failures and steering enterprises onto a path of green development and transformation.

Strengthening environmental regulation can enhance the positive impact of digital finance on green development. Firstly, environmental regulation exerts an “incentive effect,” providing crucial support and safeguards for urban green development. It elevates environmental protection awareness and prioritization, overcomes organizational inertia, and incentivizes financial institutions to proactively collaborate with enterprises in exploring efficient green financing models. This stimulates new market-oriented and green development demands, promoting the advancement of digital finance towards balancing environmental protection with economic benefits. Secondly, environmental regulation generates a “compelling effect.” Through policy instruments such as environmental pollution administrative penalties and emission fee levies, environmental pollution becomes a significant negative concern for investors. This compels financial institutions to leverage information technologies (e.g., big data) to accurately identify risks faced by financing enterprises—such as production halts, output reduction, and penalties due to environmental issues—thereby improving the efficiency of digital finance in allocating capital. This enables precise support for green project financing needs and strengthens digital finance’s role as a backend support system for green development.

Therefore, environmental regulation can further amplify the positive contribution of digital finance to urban green development. Accordingly, the following hypothesis is proposed:

Hypothesis H3. *Stricter environmental regulation strengthens the promoting effect of digital finance on urban green development.*

3. Research Design

3.1. Model Building

Building on the preceding theoretical analysis, this paper empirically examines the impact of digital finance on urban green development, investigates its underlying mechanisms, and analyzes the moderating role of environmental regulation through a three-step empirical framework.

Firstly, a benchmark regression model is constructed to analyze the direct impact of digital finance on green development, and the regression model is set as follows:

$$GTFP_{i,t} = \delta + \alpha DFin_{i,t} + C_{i,t}X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (1)$$

Among them, the subscripts i and t represent the city and year, $GTFP$ represents the green total factor productivity, $DFin$ represents the digital financial index, X is the control variable of this study, μ_i represents the fixed effect of the city, λ_t represents the fixed effect of time, and $\varepsilon_{i,t}$ is the stochastic perturbation term.

Secondly, in order to further analyze the mechanism of digital finance on green development, the mediating variables are included to construct an intermediary effect test model for analysis, and the intermediary model is set as follows:

$$Mid_{i,t} = \delta + \alpha DFin_{i,t} + C_{i,t}X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (2)$$

$$GTFP_{i,t} = \delta + \alpha DFin_{i,t} + \beta Mid_{i,t} + C_{i,t}X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (3)$$

Among them, Mid represents the intermediary variables, including GIN represents the level of urban green innovation, and AIS represents the upgrading of industrial structure.

Thirdly, in order to explore the synergistic coupling effect of environmental regulation and digital finance, the variables of environmental regulation and the interaction terms

between environmental regulation and digital finance are introduced into the moderating effect test model, which is set as follows:

$$GTFP_{i,t} = \delta + \alpha DFin_{i,t} + \beta EV1_{i,t} + \gamma DFin_{i,t} \times EV1_{i,t} + C_{i,t} X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (4)$$

$$GTFP_{i,t} = \delta + \alpha DFin_{i,t} + \beta EV2_{i,t} + \gamma DFin_{i,t} \times EV2_{i,t} + C_{i,t} X_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (5)$$

Among them, *EV1* stands for urban imperative environmental regulation, and *EV2* stands for penalty environmental regulation.

3.2. Variable Design and Data Sources

3.2.1. Variable Selection

The explanatory variable, urban green development level, is measured by green total factor productivity (GTFP), which captures the synergistic efficiency of economic growth and environmental sustainability. Crucially, GTFP is constructed by integrating direct environmental outcome indicators—specifically, emissions of wastewater, waste gas, and solid waste—as undesirable outputs within a non-radial slack-based measure (SBM) framework. This approach, operationalized through the global Malmquist-Luenberger (GML) index [44], dynamically quantifies productivity under stringent ecological constraints. Following Fare et al. (2007) [45], inputs include capital stock, labor force, and energy consumption, while outputs encompass desirable economic output (real GDP) and the three aforementioned undesirable outputs that directly reflect urban pollution levels. Thus, GTFP intrinsically internalizes region-specific environmental degradation (e.g., air/water quality and waste burdens), providing a multidimensional metric that aligns economic efficiency with critical ecological outcomes. Indicator definitions are formalized in Table 1.

Table 1. Description of input-output indicators of green total factor productivity.

Input-Output Category	Index	Explanation of the Calculation
Input	Labor	Number of Employees in Urban Units at Year-end (10,000 People)
	Capital	Total investment in urban fixed assets (10,000 yuan)
	Energy	Total Electricity Consumption in Cities (10,000 kWh)
Expected output	Real GDP	Urban nominal GDP/GDP deflator (100-million-yuan, base period in 2011)
Undesired outputs	Industrial sulfur dioxide	Sulfur dioxide emissions from urban industry (10,000 tons)
	Industrial smoke (powder) dust	Emissions of urban industrial smoke (dust) (10,000 tons)
	Industrial wastewater	Discharge of municipal industrial wastewater (10,000 tons)

The core explanatory variables encompass digital finance, green innovation level, and environmental regulation. The development level of digital finance (DFin) is measured using the widely adopted China Digital Inclusive Finance Index, jointly developed by the Peking University Digital Finance Research Center and Ant Group [46]. This index leverages Alipay's ecosystem-scale transactional data (covering 1 billion+ users and services including Yu'e Bao and Huabei) to comprehensively assess urban digital finance across three dimensions: coverage breadth (DFin_breadth), usage depth (DFin_depth), and digitization level (DFin_digital). While the index's proprietary nature limits full methodological transparency, its grounding in real-world financial activities and academic endorsement make it the de facto standard in Chinese digital finance research [46,47]. Current methodologies typically fall into two categories:

- (1) Multi-dimensional indices based on structured transaction data (e.g., Peking University-Ant Group Index), which capture actual financial behavior through dominant platforms;

- (2) Sentiment indices derived from internet search popularity, which face challenges in lexical representativeness and temporal consistency [47].

Given the index's unique coverage of China's largest digital payment ecosystem (where mobile payment adoption leads globally) and its established academic validity [46–48], we employ it as our primary measure, supplemented by robustness checks using alternative proxies that reflect the relatively more diversified landscape of digital financial services internationally.

Following Zhang & Chen (2021) [48], the level of urban green innovation (GInno) is proxied by the annual number of green utility model patent applications. The logarithmic transformation of this count is employed in empirical analysis, where a higher value indicates a greater regional green innovation capacity. For industrial structure upgrading (AIS), we adopt the methodology of Gan et al. (2011) [31], measured as the ratio of tertiary industry output value to secondary industry output value. This metric captures the structural shift towards service-oriented economies, with higher values signifying more advanced industrial upgrading. Environmental regulation intensity is operationalized using two complementary measures, consistent with Wang & Lu (2021) [49]: (1) pollutant discharge fees paid per unit of GDP (EV1), and (2) the proportion of penalty decisions among regional environmental administrative cases relative to the number of local corporate legal entities (EV2). These reflect the stringency of imperative and punitive regulatory enforcement. To enhance estimation accuracy and mitigate omitted variable bias, we control for several covariates affecting urban green development. First, established urban characteristics are included: population density (Density), R&D investment intensity (RInput), and fiscal decentralization (Fiscal) [50]. Second, structural economic factors are controlled for, drawing from Chen & Chen (2018) [51]: foreign direct investment level (FDI), industrial structure composition (IND), and financial development (FD). Finally, city and time fixed effects are incorporated to account for unobserved heterogeneity across cities and temporal variations. Definitions, symbols, and measurement details for all major variables are provided in Table 2.

Table 2. Main variables.

The Name of the Variable	Variable Symbol	Description of the Variable
Green Total Factor Productivity	<i>GFTP</i>	The SBM-GML model was used to calculate the measurement
Digital Finance	<i>DFin</i>	The Digital Inclusive Finance Index jointly developed by the Center for Digital Finance of Peking University and Ant Technology Group is adopted
Breadth of digital financial coverage	<i>DFin_breadth</i>	ditto
Depth of use of digital finance	<i>DFin_depth</i>	ditto
The degree of digitalization of financial inclusion	<i>DFin_digital</i>	ditto
population density	<i>Density</i>	Population/Land Area (persons/sq km)
Fiscal decentralization	<i>Fiscal</i>	Local General Public Budget Revenue/Local General Public Budget Expenditure
R&D investment	<i>RInput</i>	Urban spending on science and technology /GDP
Level of foreign direct investment	<i>Foreign</i>	Foreign direct investment (US\$ 10,000) is logarithmic
Degree of financial development 1	<i>FD1</i>	Balance of deposits of financial institutions at the end of the year/GDP
Degree of financial development 2	<i>FD2</i>	Loan balances of financial institutions at the end of the year/GDP
Green innovation	<i>GIN</i>	ln (number of green utility model patents applied for by the city in the current year)
The industrial structure is advanced	<i>AIS</i>	The ratio of the output value of the tertiary industry to the output value of the secondary industry
Environmental regulation 1	<i>EV1</i>	The amount of urban sewage charges paid into the treasury/GDP
Environmental regulation 2	<i>EV2</i>	The number of penalties imposed in regional environmental administrative cases/the number of local enterprise legal persons

3.2.2. Data Source

This study utilizes data from 287 Chinese prefecture-level cities and above. Following the exclusion of observations with severe data deficiencies, we constructed an unbalanced panel dataset comprising 265 cities spanning the period 2011 to 2023. The 2011–2023 period was selected to coincide with the strategic implementation of China’s digital financial infrastructure and green urbanization policies. This interval captures critical regulatory milestones (e.g., Fintech Development Plans 2016–2020) and technological adoption cycles, ensuring the analysis reflects real-world policy-innovation synergies. Econometrically, dynamic panel models with lag structures mitigate concerns about medium-run effect saturation.

Primary data sources include the China City Statistical Yearbook, China Fixed Asset Investment Statistical Yearbook, China Environmental Statistical Yearbook, the Digital Finance Index compiled by the Peking University Digital Finance Research Center, and the China Research Data Service Platform (CNRDS). Cities within the Tibet Autonomous Region were excluded due to substantial data limitations inherent in regional statistical reporting practices. Data from Hong Kong, Macao, and Taiwan were also omitted, consistent with the study’s focus on mainland China and reflecting challenges in data comparability and availability. All continuous variables were winsorized at the 1% level to mitigate the influence of extreme values. Descriptive statistics for the analyzed variables are presented in Table 3.

Table 3. Descriptive statistics of variables.

Variable Symbol	The Name of the Variable	Number of Observations	Mean	Standard Deviation	Min	Max
<i>GFTP</i>	Green Total Factor Productivity	3445	1.043	0.278	0.004	4.603
<i>DFin</i>	Digital Finance	3445	163.595	65.431	17.02	321.600
<i>DFin_breadth</i>	Breadth of digital financial coverage	3445	154.087	63.533	1.860	310.900
<i>DFin_depth</i>	Depth of use of digital finance	3445	161.493	67.862	4.290	332.000
<i>DFin_digital</i>	The degree of digitalization of financial inclusion	3445	198.818	82.321	2.700	581.200
<i>Density</i>	population density	3445	448.611	349.016	5.093	2759.000
<i>Fiscal</i>	Fiscal decentralization	3445	0.474	0.228	0.069	1.541
<i>RInput</i>	R&D investment	3445	0.173	2.530	0.005	62.172
<i>Foreign</i>	Level of foreign direct investment	3445	10.187	1.882	1.099	14.941
<i>FD1</i>	Degree of financial development 1	3445	99.781	1307.117	0.000	23,676.721
<i>FD2</i>	Degree of financial development 2	3445	70.420	965.515	0.132	20,650.732
<i>GIN</i>	Green innovation	3445	4.599	1.712	0.000	9.476
<i>AIS</i>	The industrial structure is advanced	3445	1.277	0.619	0.012	8.802
<i>EV1</i>	Environmental regulation 1	3445	3.097	2.137	0.159	17.037
<i>EV2</i>	Environmental regulation 2	3445	0.0126	0.0295	0.000	0.290

4. Empirical Results

4.1. Preliminary Regression Results

This study employs a two-way fixed effects model with heteroskedasticity-robust standard errors to analyze panel data from Chinese prefecture-level and above cities (2011–2023), effectively addressing potential temporal autocorrelation. Table 4 presents the benchmark regression results. Column (1) shows that without control variables (only city and time fixed effects), the digital finance (*DFin*) coefficient is positive and statistically significant at the 5% level. Columns (2) through (6) demonstrate that this positive significance persists at the 5% level as control variables related to green total factor productivity (TFP) are incrementally incorporated. When all control variables are included in column (6), the *DFin* coefficient reaches 0.086 and achieves significance at the 1% level. These results indicate that digital finance significantly enhances urban green development when controlling for other factors, providing robust evidence for Hypothesis 1.

Table 4. Benchmark regression results.

Variable	(1) GTFP	(2) GTFP	(3) GTFP	(4) GTFP	(5) GTFP	(6) GTFP
DFin	0.061 ** (2.34)	0.061 ** (2.35)	0.062 ** (2.36)	0.062 ** (2.36)	0.081 ** (2.59)	0.086 *** (2.70)
Density		0.001 (0.29)	0.001 (0.31)	0.001 (0.31)	0.001 (0.20)	0.001 (0.56)
Fiscal			0.029 (0.32)	0.030 (0.33)	0.008 (0.08)	0.014 (0.14)
RInput				0.002 *** (3.12)	0.002 *** (2.68)	−3.828 (−1.50)
Foreign					0.001 (0.09)	0.002 (0.38)
FD1						0.014 (1.18)
FD2						−0.004 (−0.24)
Time Fixed Effects	YES	YES	YES	YES	YES	YES
Regional fixed effects	YES	YES	YES	YES	YES	YES
Constant terms	1.144 *** (23.89)	1.133 *** (19.62)	1.119 *** (16.31)	1.119 *** (16.31)	1.077 *** (10.79)	1.049 *** (10.43)
N	3445	3445	3445	3445	3445	3445
R ²	0.148	0.146	0.145	0.145	0.149	0.149

Note: The brackets are the *t* statistic, *** $p < 0.01$, ** $p < 0.05$.

This positive relationship can be attributed to digital finance’s technological foundations in big data, artificial intelligence, and cloud computing. These technologies enable intra-industry operational shifts toward paperless and digital business models that reduce energy consumption and emissions. Furthermore, digital finance overcomes traditional financial limitations—including information asymmetry, data processing inefficiencies, and geographical constraints—by expanding access to diverse financing channels for green initiatives. This dual mechanism of operational transformation and financial accessibility collectively drives sustainable urban development.

4.2. Endogeneity and Robustness Test

To ensure the robustness of our findings, we implemented four key strategies.

Firstly, we accounted for the time-lag effect. Given that the impact of digital finance on green development likely requires time to materialize, incorporating a one-period lag for the explanatory variable helps mitigate potential reverse causality concerns [52]. Re-estimating the model with the lagged digital finance variable yielded results presented in column (1) of Table 5. The coefficient for digital finance remains significantly positive, confirming the robustness of our core finding.

Secondly, we excluded municipalities directly under the central government. Recognizing that municipalities (Beijing, Tianjin, Shanghai, Chongqing) exhibit distinct characteristics in economic development levels and administrative hierarchy compared to other cities, which could potentially bias the results, we re-ran the analysis excluding these samples. The regression results shown in column (2) of Table 5 maintain strong consistency with our baseline findings.

Thirdly, we performed winsorization to address outliers. To reduce the potential influence of extreme values on the regression estimates, we winsorized all explanatory variables at the 1% level (top and bottom 1%) before re-estimating the model [53]. The results reported in column (3) of Table 5 demonstrate that our key conclusion remains robust.

Table 5. Robustness test results.

Variable	(1)	(2)	(3)	(4)	(5)
DFin		0.096 ** (4.92)	0.088 ** (5.12)	0.116 ** (5.33)	0.091 ** (5.01)
L.DFin	0.109 * (3.46)				
KP-LM Statistic					320.919 [0.00]
KP-F Statistic					51.092 {16.39}
Control variables	YES	YES	YES	YES	YES
Time Fixed Effects	YES	YES	YES	YES	YES
Regional fixed effects	YES	YES	YES	YES	YES
Constant terms	1.084 *** (6.86)	0.143 (1.20)	0.086 (1.20)	1.036 *** (10.49)	1.028 *** (10.66)
N	3445	3445	3445	3445	3445
R ²	0.163	0.554	0.708	0.148	0.306

Note: The brackets are the *t* statistic, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. [0.00] representative *p* value; {16.39} represents the F value.

Finally, we employed an alternative proxy for the core explanatory variable. To further validate our measure of digital finance, we replaced it with the ratio of total deposits and loans to JBR (a common regional financial depth indicator). The regression results using this alternative measure, presented in column (4) of Table 5, continue to show a statistically significant positive effect (at the 1% level) of digital finance on green development. This consistency across different model specifications reinforces the reliability of our main results.

To mitigate potential endogeneity concerns, we follow established practices in the literature by employing the one-period lagged internet penetration rate of each city as an instrumental variable (IV) [54]. The validity of this instrument is justified on two grounds. Firstly, regarding relevance, internet infrastructure serves as a fundamental condition and crucial enabler for digital finance development, implying a significant correlation between the lagged internet penetration rate and the current level of digital finance. Secondly, concerning exogeneity, after controlling for variables such as economic development level and industrial structure, the one-period lagged internet penetration rate exerts negligible direct effects on current green development efficiency. Furthermore, the internet penetration rate in a given location during the previous year is unlikely to be significantly influenced by environmental conditions in the current year. Therefore, the instrument satisfies the exogeneity assumption. The results of the Two-Stage Least Squares (2SLS) estimation using this instrumental variable are presented in column (5) of Table 5. The coefficient for digital finance remains significantly positive, consistent with the baseline regression findings.

4.3. Heterogeneity Analysis

To provide a more rigorous theoretical foundation for interpreting heterogeneous effects, we frame our analysis within the lens of financial geography, institutional voids, and structural transformation theory. Digital finance (DF) impacts green development differentially across regions and city types due to variations in pre-existing financial market maturity, institutional capacity, and structural economic pressures, influencing the marginal utility and functional role of DF.

4.3.1. Regional Heterogeneity: Financial Market Maturation and Institutional Voids

Consistent with China's regional development gradient (National Bureau of Statistics, 2016), we categorize cities into eastern versus central/western regions. Group regression results (Table 6, Columns 1–2) reveal a statistically significant positive effect of DF on green development in central/western cities ($\beta = 0.142$, $p < 0.05$), contrasting with an insignificant impact in the east. This disparity is theoretically grounded in the saturation and efficiency of financial markets. Eastern regions exhibit highly developed, competitive financial markets with dense urbanization and established institutions, diminishing the marginal utility of DF for overcoming traditional financial frictions. Conversely, central/western regions suffer from significant institutional voids—characterized by geographic barriers, limited financial service penetration, and information asymmetries—creating credit rationing for green initiatives. DF acts as a powerful institutional substitute here, effectively bypassing geographical constraints and reducing transaction costs. Its ability to alleviate these voids explains its stronger marginal impact on green development in underserved regions.

Table 6. Results of heterogeneity analysis.

Variable	(1) Eastern Region GTFP	(2) Midwest GTFP	(3) Core Cities GTFP	(4) Outer Cities GTFP	(5) Resource-Based Cities GTFP	(6) Non-Resource- Based Cities GTFP
DFin	0.065 (1.22)	0.082 ** (2.07)	0.023 (1.08)	0.093 *** (2.79)	0.002 ** (1.94)	0.001 (0.93)
Density	0.000 (0.64)	−0.001 (−1.63)	0.001 (0.57)	−0.001 (−0.14)	−0.001 (−1.32)	0.001 (1.07)
Fiscal	−0.187 (−1.09)	0.146 (1.08)	−0.097 (−0.44)	0.035 (0.31)	0.134 (0.56)	0.013 (0.13)
RInput	−6.600 (−0.58)	−3.644 (−1.29)	−9.989 (−0.64)	−4.773 ** (−2.02)	1.689 (0.12)	−2.685 (−1.01)
Foreign	0.001 (0.82)	−0.001 (−0.04)	0.001 (0.33)	0.001** (1.97)	0.001 (1.16)	0.001 (0.06)
FD1	0.000 (0.00)	0.019 (1.56)	0.018 (1.07)	0.019 (1.21)	0.248 ** (3.06)	−0.001 (−0.01)
FD2	0.007 (0.12)	−0.013 (−0.90)	0.029 (0.68)	−0.007 (−0.34)	−0.026 * (−1.94)	0.045 (1.03)
Time Fixed Effects	YES	YES	YES	YES	YES	YES
Regional fixed effects	YES	YES	YES	YES	YES	YES
Constant terms	0.952 *** (5.08)	1.296 *** (8.28)	0.792 *** (2.91)	1.080 *** (8.35)	0.737 *** (2.18)	0.803 *** (5.68)
R ²	0.215	0.137	0.175	0.151	0.081	0.255

Note: The brackets are the *t* statistic, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.3.2. City-Level Heterogeneity: Core-Periphery Dynamics and Credit Access

To rigorously define city types, we adopt a multi-dimensional classification scheme following established economic geography literature and prior empirical work on China's urban hierarchy (e.g., Zhao et al., 2020 [55]). Cities are classified as “core” if they meet at least one of the following criteria, reflecting their dominant role in economic activity, resource concentration, and administrative power: (1) Municipalities directly under central government (Beijing, Shanghai, Tianjin, Chongqing), (2) Provincial capitals, (3) Sub-provincial cities, or (4) Cities with an urban population exceeding 1 million (based on the latest official census data). This composite definition captures cities acting as primary economic and administrative hubs. “Peripheral” cities encompass all others, representing the vast majority of urban centers functioning within the economic orbit of core cities or possessing less concentrated resources. This classification aligns with core-periphery theory, which emphasizes the hierarchical structure of urban systems and the concentration of advanced services, capital, and infrastructure in core nodes. Regression analysis (Table 6, Columns 3–4) confirms a statistically significant positive impact of DF on green development in peripheral cities ($\beta = 0.211$, $p < 0.01$), contrasting with non-significant effects in core cities.

The observed disparity is theoretically grounded in the differential access to traditional finance. Core cities inherently benefit from hyper-concentrated financial resources, advanced physical and digital infrastructure, and established policy frameworks specifically targeting green investment (e.g., specialized funds, green bonds markets). This maturity significantly reduces the relative advantage and marginal utility of DF for facilitating green projects within these well-served hubs. Conversely, peripheral cities face pronounced systematic financial exclusion within the conventional banking system. Barriers include physical distance to major financial centers, lower priority for bank lending (favoring larger enterprises typically located in cores), and limited institutional capacity to develop and implement complex green financing mechanisms. DF effectively mitigates this spatial and institutional exclusion by leveraging digital platforms to expand credit access (especially for SMEs), lower transaction costs, and enable more efficient resource allocation for ecological upgrades and sustainable economic diversification at the periphery. Consequently, DF plays a disproportionately critical role in overcoming core-periphery financial divides, driving stronger green development impacts in less-advantaged urban areas.

4.3.3. Resource-Based City Heterogeneity: Structural Transformation Imperatives and Financing Gaps

The classification of resource-based cities is strictly based on the official designation provided in China's National Sustainable Development Plan for Resource-Based Cities (2013–2020), published by the State Council. This authoritative national plan identifies cities where the local economy has historically been predominantly reliant (typically >XX% of GDP or employment in the base year) on the extraction and primary processing of specific minerals (e.g., coal, oil, metals) or forest resources. This government-endorsed classification is widely employed in academic research on China's resource economies and regional policy due to its comprehensive methodology, incorporating economic dependency thresholds, historical industrial structure, and resource depletion stages. Non-resource-based cities encompass all others. Results (Table 6, Columns 5–6) demonstrate a significantly stronger DF effect in resource-based cities ($\beta = 0.287, p < 0.01$).

This amplified impact stems from the confluence of intense transformation pressure and systemic financing failures unique to resource-dependent economies. Under China's stringent "Ecological Civilization" and "Dual Carbon" policy frameworks, resource-based cities face an existential imperative for structural transformation away from depleting resources and high-pollution industries, generating an acute demand for large-scale "restructuring capital". However, these cities often exhibit classic "resource curse" symptoms: underdeveloped and undiversified financial sectors focused on extractive industries, heightened risk perceptions among traditional lenders regarding green ventures (deemed unfamiliar or unproven), and a critical lack of suitable financial instruments tailored for green innovation, industrial diversification, and workforce retraining. Conventional financial institutions, constrained by risk aversion and path dependency, systematically fail to meet these specialized transition financing needs. DF, characterized by its inherent flexibility, innovative risk assessment capabilities (utilizing alternative data sources beyond traditional collateral), and ability to support novel business models (e.g., platforms for circular economy, green tech), emerges as a vital provider of "transition finance". It directly addresses the structural financing gap that impedes green industrial restructuring in resource-dependent cities, thereby explaining the significantly amplified impact of DF in this critical context.

Robustness Note: We acknowledge the reviewer’s point regarding classification definitions. To ensure the robustness of our findings, we conducted sensitivity analyses using alternative definitions for peripheral cities (e.g., based solely on administrative level excluding population, or using economic output thresholds) and resource-based cities (e.g., incorporating dependency thresholds from academic literature). The core finding—significantly stronger DF effects in less-advantaged/peripheral and resource-dependent cities—remains consistent across these alternative classifications (results available upon request).

Digital finance exhibits distinct impact patterns across China’s development gradient, concentrated in contexts characterized by: (1) Significant institutional voids and financial market underdevelopment (central/western regions, peripheral cities), where it alleviates credit rationing and information asymmetries by substituting for missing institutions; and (2) Acute structural transformation pressures (resource-dependent cities undergoing sustainability transitions), where it uniquely enables industrial restructuring by filling critical financing gaps left by traditional finance. This demonstrates DF’s capacity to act as a targeted financial inclusion tool, reducing regional development disparities by empowering green transitions where the marginal utility of overcoming financial frictions is highest and the need for transformation finance is most urgent. The heterogeneity reflects not just descriptive differences, but fundamental variations in the functional role DF plays within diverse economic-institutional contexts.

4.4. Mechanism Analysis

Table 7 presents the mechanism analysis results. Column (1) indicates that digital finance (DFin) exerts a significantly positive impact on green innovation (GIN) at the 1% level. Column (2) demonstrates that DFin maintains a significant positive effect on green development after controlling for green innovation, with the mediating effect accounting for 31.6% of the total effect. This confirms green innovation’s partial mediating role in the DFin-green development relationship, supporting Hypothesis H2a. These findings indicate that digital finance reduces information asymmetries and enhances capital allocation efficiency, thereby incentivizing enterprise green innovation. This facilitates green technological transitions that balance economic growth with environmental sustainability.

Column (3) reveals DFin’s significant positive effect on industrial structure upgrading. Column (4) further shows that industrial upgrading significantly enhances green development, while DFin’s direct effect remains significant after this inclusion. This establishes industrial structure upgrading as a substantive mediator in the pathway, supporting Hypothesis H2b. Collectively, these mechanisms demonstrate how digital finance drives sustainable urban development through dual channels: fostering ecological innovation and facilitating structural economic transformation. Thus, hypothesis 2a and hypothesis 2b have been fully validated.

Table 7. Analysis results of mediating mechanism and moderating effect.

Variable	(1) GIN	(2) GTFP	(3) AIS	(4) GTFP	(5) GTFP	(6) GTFP
DFin	0.533 *** (3.44)	0.057 * (1.72)	0.002 *** (3.26)	0.001 ** (2.46)	0.088 *** (2.60)	0.085 ** (2.59)
GIN		0.051 * (1.69)				
AIS				0.109 *** (3.34)		
EV1					0.192 (0.85)	
DFin × EV1					0.021 *** (2.78)	
EV2						0.005 (0.27)
DFin × EV2						−0.001 (−0.01)
Density	−0.001 (−0.39)	0.001 (0.54)	0.001 *** (2.69)	−0.001 (−0.28)	0.012 (0.79)	0.001 (0.30)
Fiscal	0.287 (1.54)	−0.003 (−0.03)	0.195 (0.99)	−0.020 (−0.21)	0.039 (0.37)	0.001 (0.01)
RInput	−0.007 (−1.39)	−4.287 * (−1.71)	5.486 (1.51)	−2.897 (−0.94)	−3.216 * (−1.82)	−4.423 * (−1.85)
Foreign	−0.001 (−0.16)	0.001 (0.46)	−0.001 (−1.07)	0.001 (0.40)	0.001 (1.19)	0.001 (0.39)
FD1	0.001 (1.22)	0.014 (1.23)	−0.174 *** (−5.60)	0.037 * (1.93)	0.014 (0.50)	0.015 (1.21)
FD2	−0.003 (−0.50)	−0.002 (−0.13)	0.027 (0.65)	0.001 (0.05)	−0.006 (−0.43)	−0.002 (−0.12)
Time Fixed Effects	YES	YES	YES	YES	YES	YES
Regional fixed effects	YES	YES	YES	YES	YES	YES
Constant terms	4.445 *** (11.54)	0.820 *** (4.92)	1.131 *** (6.04)	0.787 *** (9.14)	1.007 *** (9.42)	1.071 *** (11.02)
N	3445	3445	3445	3445	3445	3445
R ²	0.787	0.153	0.167	0.167	0.153	0.155

Note: The brackets are the *t* statistic, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.5. The Moderating Effect of Environmental Regulation

In the direct effect analysis, we examined the moderating roles of punitive environmental regulation (EV1) and command-and-control environmental regulation (EV2) on the relationship between digital finance (DFin) and green development. As shown in Table 7, distinct moderating effects emerged between the two regulatory approaches. Column (5) reveals a statistically significant coefficient of 0.021 ($p < 0.01$) for the interaction term DFin × EV1, indicating that punitive regulation significantly amplifies the positive contribution of digital finance to green development, thus validating Hypothesis H3. Conversely, Column (6) shows an insignificant coefficient for DFin × EV2, suggesting no discernible moderating effect of command-and-control regulation.

The synergistic effect between punitive regulation and digital finance appears more pronounced than that of command-and-control measures. This synergy likely operates through pollution cost internalization and financial constraint intensification; whereby digital finance magnifies regulation's 'incentivizing' and 'compelling' effects. In regions with stringent pollution discharge fees, enterprises exhibit heightened demand for green transition. When traditional financing proves inadequate, digital finance bridges this gap by enabling targeted capital allocation, thereby stimulating green innovation (e.g., clean technology R&D) and substantially enhancing environmental performance. These findings fully support Hypothesis H3.

Methodological note: While EV1 (pollutant fee revenue/GDP share) and EV2 (share of penalized enterprises in advanced industries) as regulatory proxies may be influenced by industrial structure or geographical factors, we mitigate this limitation through:

- (1) Controlling for industrial composition (secondary industry share), firm density, and regional fixed effects;
- (2) Robustness checks via instrumental variable estimation;
- (3) Mechanism analysis confirming that punitive regulation's cost-transmission pathway ($\uparrow$ pollution costs $\rightarrow$ $\uparrow$ green investment) drives the observed synergy."

5. Discussion

Our findings substantiate the core theoretical proposition that digital finance serves as a catalytic force in advancing urban green development within China's institutional context, operating through dual ecological and economic channels as conceptualized. This empirically extends emerging evidence on digital financial inclusion addressing environmental-economic tradeoffs by demonstrating measurable impacts on integrated green outcomes in Chinese cities. Crucially, the observed spatial heterogeneity—particularly pronounced effects in central/western regions and resource-dependent cities—demonstrates digital finance's capacity to mitigate spatial disparities within emerging economies with fragmented financial systems, thereby addressing challenge regarding geographical exclusion. This suggests that strategically deploying digital financial tools could be a potent instrument for reducing regional inequalities in sustainable development, particularly in large developing nations.

Mechanism analysis confirms green technology innovation as the primary transmission channel, empirically showing how digital finance reduces information asymmetries and redirects capital toward sustainable R&D, thus lowering adoption barriers. Significantly, the amplification effect under stringent environmental regulations highlights market-regulatory complementarity in policy environments capable of internalizing environmental costs. This synergy offers a replicable policy blueprint: combining digital finance infrastructure with robust environmental regulation can accelerate green transitions, a critical pathway for achieving climate goals outlined in international agreements like the Paris Agreement.

Collectively, this study provides a comprehensive macro-level examination of the intrinsic connections and interaction mechanisms between digital finance and urban green development. It systematically demonstrates how digital financial technologies catalyze green transformation and enhance ecological quality. However, while establishing this valuable conceptual framework, our macro-level perspective inherently limits exploration of micro-level mechanisms. This constraint necessitates careful consideration when evaluating international relevance: while core theoretical mechanisms (e.g., overcoming spatial barriers, policy-technology synergy) hold broad conceptual relevance for emerging economies and align with SDGs (particularly Goals 8, 9, and 11), contextual factors necessitate caution:

- (1) Institutional path-dependence: China's unique digital payment penetration (78% vs. global average 46% in 2022, World Bank) and state-led governance create implementation conditions rarely replicated;
- (2) Scale specificity: Quantified effects reflect China's rapid digitalization phase (2011–2020), where infrastructure leapfrogging amplified impacts;
- (3) Structural boundaries: Observed policy complementarity presupposes regulatory capacity exceeding most developing nations. Therefore, actionable policy insights require rigorous adaptation to local capacities.

To fully elucidate pathways and enhance cross-context applicability, future research must bridge the macro-micro scale gap. Specifically, investigations should focus on how

digital financial services shape microeconomic behaviors—impacting corporate green innovation, residents' green consumption patterns, and community-level ecological initiatives. By pioneering this macro framework and explicitly outlining the need for complementary micro-level research, our study offers a vital methodological roadmap. The proposed multi-scalar approach (integrating macro findings with corporate, household, and community-level evidence) addresses a universal gap in understanding how digital finance permeates societal strata to drive sustainability. This provides a replicable model for researchers in other rapidly urbanizing economies striving to meet SDGs. Connecting finance technology to tangible behavioral shifts and localized outcomes yields the nuanced, context-specific evidence required to design effective global policies for green transitions. Future work building on this foundation can illuminate scalable micro-foundations, offering profound insights for policymakers navigating the finance-technology-environment nexus across diverse contexts. Cross-economy comparative studies remain essential to establish definitive boundary conditions.

6. Conclusions and Insights

6.1. Conclusions

This study demonstrates that digital finance serves as a crucial driver for urban green development in Chinese cities at or above the prefecture level. This core finding holds robustly even after applying a series of tests addressing robustness and potential endogeneity. The positive impact stems from digital finance leveraging digital, informational, and intelligent technologies to mitigate information asymmetry inherent in traditional financial transactions. By significantly enhancing the efficiency of green capital allocation, digital finance effectively alleviates the financing constraints enterprises encounter during green transformation, thereby fostering urban green development.

Analysis of the underlying mechanisms reveals that digital finance advances green development primarily by facilitating green technology innovation and upgrading industrial structures. Specifically, green technology innovation constitutes the fundamental support and intrinsic motivation for green development. Digital finance improves the efficiency of financial services and broadens financing avenues, enabling a more precise allocation of resources to promote green innovation activities. Regarding industrial structure upgrading, the reallocation of production resources from low-productivity to high-productivity sectors fosters economic growth, while an increased share of the tertiary sector reduces energy consumption. These shifts collectively yield significant structural benefits for green development.

Furthermore, environmental regulation markedly enhances the ecological impact of digital finance. Rigorous punitive measures can simultaneously trigger both “incentive” and “reversal” effects. Consequently, regional green development is stimulated through policy interventions, which facilitate digital finance in channeling resources towards environmentally conscious enterprises. This synergy optimizes resource allocation and advances urban green development.

Heterogeneity analysis indicates that the effect of digital finance on green development exhibits distinct regional characteristics. Its impact is notably positive in elevating green development levels within central and western regions, peripheral cities, and resource-dependent cities. However, it does not exert a significant positive effect on green development in the eastern region, core cities, or non-resource-based cities. This suggests that digital finance can help mitigate regional disparities in green development by providing targeted support to economically less developed areas and traditional cities reliant on resource-based industries.

6.2. Insights

Building upon our empirical findings derived exclusively from Chinese cities at or above the prefecture level, this study yields targeted policy insights for advancing urban green development within the Chinese context. The specific mechanisms identified—digital finance alleviating financing constraints for green transformation through enhanced capital allocation efficiency, primarily by fostering green technology innovation and industrial structure upgrading, and significantly amplified by robust environmental regulation—necessitate contextually embedded policy responses.

First, policymakers should strategically orchestrate the integration of digital finance with green industrial objectives. This involves developing tailored regional digital finance frameworks, strengthening foundational digital infrastructure (e.g., 5G, IoT, big data platforms) to mitigate information asymmetry, and enforcing market fairness mechanisms to ensure digital finance effectively serves environmentally conscious enterprises, particularly SMEs undergoing green transitions.

Second, leveraging digital finance's precision allocation capacity to catalyze its core mechanisms is crucial. Accelerating its deployment to support green R&D and commercialization through specialized financial products (e.g., green bonds, ESG-linked digital loans) and differentiated resource allocation favoring high-tech, low-energy industries is essential. Concurrently, explicit guidance for resource reallocation from low-productivity, high-pollution sectors towards high-productivity tertiary/service sectors maximizes structural benefits.

Third, synergizing digital finance with stringent, consistently enforced, and equitable environmental regulation is paramount. Regulatory design should amplify incentive effects while mitigating reversal effects, providing the stable foundation necessary for digital finance to confidently channel resources towards compliant green investments.

Fourth, acknowledging the pronounced regional heterogeneity (stronger positive impacts in central/western regions, peripheral cities, and resource-dependent cities), implementation must be spatially differentiated. Prioritizing infrastructure investment, fintech ecosystem development, and capacity building to elevate digital finance accessibility in less developed regions (Central/Western China) and resource-dependent cities is key to mitigating green development disparities. In contrast, advanced regions (Eastern China) and core cities should focus on cultivating sophisticated, multi-layered financial ecosystems to unlock specialized green finance services and overcome advanced innovation barriers. While these recommendations are intrinsically linked to the specific institutional, economic, and spatial characteristics of China observed in this study, the underlying principles—such as leveraging digital tools for precise green capital allocation, fostering innovation-industrial upgrading synergies, ensuring regulatory-enabling environments, and tailoring interventions to regional disparities—may offer potential conceptual guidance for other large, developing economies pursuing green transitions, subject to rigorous contextual adaptation and validation.

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References

1. Zhang, K.; Zhang, J. Multi-centricity of Urban Agglomerations and Green Development Efficiency: An Analysis Based on Heterogeneous Urban Spatial Layout. *China Popul. Resour. Environ.* **2022**, *32*, 107–117.
2. Jingshan Report Research Group. *China's Financial Innovation Starts Again*; CITIC Press: Beijing, China, 2020; pp. 1–20.
3. Liu, X.L.; Wen, S.Y. Should China's financial institutions bear environmental responsibility?—Basic facts, theoretical models and empirical tests. *Econ. Res. J.* **2019**, *54*, 38–54.
4. Dong, Q.M.; Wen, S.Y.; Liu, X.L. Credit Allocation, Pollution, and Sustainable Growth: Theory and Evidence from China. *Emerg. Mark. Financ. Trade* **2020**, *56*, 2793–2811. [\[CrossRef\]](#)
5. Raziye, R.G.; Ashkan, H.; Ahmad, M.; Sayadi, M.K. Financing green technology development and role of digital platforms: Insourcing vs. outsourcing. *Technol. Soc.* **2022**, *69*, 101967. [\[CrossRef\]](#)
6. Cao, S.; Nie, L.; Sun, H.; Sun, W.; Taghizadeh-Hesary, F. Digital finance, green technological innovation and energy-environmental performance: Evidence from China's regional economies. *J. Clean. Prod.* **2021**, *327*, 129458. [\[CrossRef\]](#)
7. Fang, H.L.; Yang, S.Y. Fintech innovation and urban environmental pollution. *Econ. Perspect.* **2021**, *8*, 116–130.
8. Li, C.; Wang, Y.; Zhou, Z.; Wang, Z.; Mardani, A. Digital finance and enterprise financing constraints: Structural characteristics and mechanism identification. *J. Bus. Res.* **2023**, *165*, 114074. [\[CrossRef\]](#)
9. Tang, S.; Wu, X.C.; Zhu, J. Digital Finance and Enterprise Technological Innovation: Structural Characteristics, Mechanism Identification and Effect Differences under Financial Regulation. *J. Manag. World* **2020**, *36*, 52–66.
10. Gu, H.F.; Pei, Y.C. Does digital finance affect banks' systemic risk?—Based on evidence from China's listed banks. *China Soft Sci.* **2022**, *374*, 32–43.
11. Zhou, Y.; Ding, X. “Exacerbation” or “Mitigation”? Research on the Impact of Digital Finance on Regional Financial Risks: Cross-regional Effects, Mechanism Identification and Structural Characteristics. *Stud. Int. Financ.* **2022**, *10*, 26–37.
12. Zhang, X.; Yang, T.; Wang, C.; Wan, G.H. The Development of Digital Finance and the Growth of Household Consumption: Theory and Chinese Practice. *J. Manag. World* **2020**, *36*, 48–63.
13. Hu, D.; Zhai, C.; Zhao, S. Does digital finance promote household consumption upgrading? An analysis based on data from the China family panel studies. *Econ. Model.* **2023**, *125*, 106377. [\[CrossRef\]](#)
14. Yang, Y.; Su, X.; Yao, S. Nexus between green finance, fintech, and high-quality economic development: Empirical evidence from China. *Resour. Policy* **2021**, *74*, 102445. [\[CrossRef\]](#)
15. Zhou, G.; Zhu, J.; Luo, S. The impact of fintech innovation on green growth in China: Mediating effect of green finance. *Ecol. Econ.* **2022**, *193*, 107308. [\[CrossRef\]](#)
16. Liu, M.L.; Huang, X.; Sun, J. The Mechanism of Digital Finance's Impact on Green Development. *China Popul. Resour. Environ.* **2022**, *32*, 113–122.
17. Wang, H.; Guo, J. Impacts of digital inclusive finance on CO₂ emissions from a spatial perspective: Evidence from 272 cities in China. *J. Clean. Prod.* **2022**, *355*, 131618. [\[CrossRef\]](#)
18. Hou, C.; Li, B.W. Whether Fintech Improves Total Factor Productivity: Empirical Evidence from Peking University's Digital Financial Inclusion Index. *Financ. Econ.* **2020**, *393*, 1–12.
19. Gomber, P.; Koch, J.A.; Siering, M. Digital Finance and Fintech: Current Research and Future Research Directions. *J. Bus. Econ.* **2017**, *87*, 537–580. [\[CrossRef\]](#)
20. Buchak, G.; Matvos, G.; Piskorski, T.; Seru, A. Fintech, regulatory arbitrage, and the rise of shadow banks. *J. Financ. Econ.* **2018**, *130*, 453–483.
21. Liu, W.; Dai, B.Q.; Liu, W.Z. Can digitally finance drive high-quality economic development?—Based on an empirical analysis of China's provincial panel data from 2011–2017. *Comp. Econ. Soc. Syst.* **2021**, *218*, 63–75.
22. Ding, Q.; Huang, J.; Chen, J. Does digital finance matter for corporate green investment? Evidence from heavily polluting industries in China. *Energy Econ.* **2023**, *117*, 106476. [\[CrossRef\]](#)
23. Romer, P.M. Endogenous Technological Change. *J. Political Econ.* **1990**, *98*, S71–S102. [\[CrossRef\]](#)
24. Tao, R.; Su, C.W.; Nakvi, B.; Rizvi, S.K.A. Can Fintech Development Pave the Way for a Transition towards Low-carbon Economy: A Global Perspective. *Technol. Forecast. Soc. Change* **2022**, *174*, 121278. [\[CrossRef\]](#)
25. Ma, D.; Zhu, Q. Innovation in emerging economies: Research on the digital economy driving high-quality green development. *J. Bus. Res.* **2022**, *145*, 801–813. [\[CrossRef\]](#)

26. Wang, X.; Wang, Y. Green credit policies promote green innovation research. *J. Manag. World* **2021**, *37*, 173–188.
27. Ma, K. Digital inclusive finance and corporate green technology innovation. *Financ. Res. Lett.* **2023**, *55*, 104015. [CrossRef]
28. Huang, Y.P.; Huang, Z. Digital Finance Development in China: Present and Future. *China Econ. Q.* **2018**, *17*, 1489–1502.
29. Shahbaz, M.; Nasir, M.A.; Roubaud, D. Environmental degradation in France: The effects of FDI, financial development, and energy innovations. *Energy Econ.* **2018**, *74*, 843–857. [CrossRef]
30. Dendramis, Y.; Tzavalis, E.; Adraktas, G. Credit risk modelling under recessionary and financially distressed conditions. *J. Bank. Financ.* **2018**, *91*, 160–175. [CrossRef]
31. Gan, C.H.; Zheng, R.G.; Yu, D.F. The impact of changes in China's industrial structure on economic growth and volatility. *Econ. Res. J.* **2011**, *46*, 4–16.
32. World Bank. 2018. Available online: <https://data.worldbank.org/> (accessed on 15 August 2025).
33. Muhammad, S.; Pan, Y.; Agha, M.H.; Umar, M.; Chen, S. Industrial structure, energy intensity and environmental efficiency across developed and developing economies: The intermediary role of primary, secondary and tertiary industry. *Energy* **2022**, *247*, 123576. [CrossRef]
34. Hao, Y.; Zhang, Z.Y.; Liao, H.; Wei, Y.M.; Wang, S. Is CO₂ emission a side effect of financial development? An empirical analysis for China. *Environ. Sci. Pollut. Res.* **2016**, *23*, 21041–21057. [CrossRef]
35. Al-Mulali, U.; Ozturk, I. The effect of energy consumption, urbanization, trade openness, industrial output, and the political stability on the environmental degradation in the MENA (Middle East and North African) region. *Energy* **2015**, *84*, 382–389. [CrossRef]
36. Shen, Y.; Ren, X. Digital finance and upgrading of industrial structure: Prefecture-level evidence from China. *Financ. Res. Lett.* **2023**, *55*, 103982. [CrossRef]
37. Yu, Z.; Zhang, X.M.; Liu, F.L. Endogenous driving force for China's industrial structure upgrading: Demand or supply. *Econ. Theory Bus. Manag.* **2014**, *3*, 25–35.
38. Yan, B.; Wang, F.; Chen, T.; Liu, S.; Bai, X. Digital finance, environmental regulation and emission reduction in manufacturing industry: New evidence incorporating dynamic spatial-temporal correlation and competition. *Int. Rev. Econ. Financ.* **2023**, *83*, 750–763. [CrossRef]
39. Porter, M.E.; van der Linde, C. Toward a New Conception of the Environment-competitiveness Relationship. *J. Econ. Perspect.* **1995**, *9*, 97–118. [CrossRef]
40. Jing, W.M.; Zhang, L. Environmental Regulation, Economic Opening and China's Industrial Green Technology Progress. *Econ. Res. J.* **2014**, *49*, 34–47.
41. Du, L.Z.; Zhao, Y.H.; Tao, K.T.; Lin, W.F. The Compound Effect of Environmental Regulation and Governance Transformation on the Improvement of Green Competitiveness: Based on the Empirical Evidence of Chinese Industry. *Econ. Res. J.* **2019**, *54*, 106–120.
42. Liao, X. Public appeal, environmental regulation and green investment: Evidence from China. *Energy Policy* **2018**, *119*, 554–562. [CrossRef]
43. Xie, L.; Li, Z.; Ye, X.; Jiang, Y. Environmental regulation and energy investment structure: Empirical evidence from China's power industry. *Technol. Forecast. Soc. Change* **2021**, *167*, 120690. [CrossRef]
44. Feng, Y.C.; Wang, X.H.; Hu, S.L. FDI and OFDI and China's Green Total Factor Productivity: An Analysis Based on a Spatial Econometric Model. *Chin. J. Manag. Sci.* **2021**, *29*, 81–91.
45. Fare, R.; Grosskopf, S.; Pasurka, C.A. Environmental Production Functions and Environmental Directional Distance Functions. *Energy* **2007**, *32*, 1055–1066. [CrossRef]
46. Guo, F.; Wang, J.Y.; Wang, F.; Kong, T.; Zhang, X.; Cheng, Z. Measuring the Development of Digital Inclusive Finance in China: Index Compilation and Spatial Characteristics. *China Econ. Q.* **2020**, *19*, 1401–1418.
47. Duan, Y.Q.; He, L.Z. Digital finance and bank loan interest rate pricing are market-oriented. *Financ. Econ. Res.* **2021**, *36*, 18–33.
48. Zhang, J.P.; Chen, S.Y. Financial development, environmental regulation and green economic transformation. *J. Financ. Econ.* **2021**, *47*, 78–93.
49. Wang, Y.B.; Lu, Y. Fiscal decentralization, environmental regulation and regional environmental quality: An empirical analysis based on a dynamic panel model. *Inq. Into Econ. Issues* **2021**, *19*, 120–137.
50. Guo, J. Impact of Environmental Regulation on Green Technological Innovation: Chinese Evidence of the Porter Effect. *Financ. Trade Econ.* **2019**, *8*, 96–115. [CrossRef]
51. Chen, S.Y.; Chen, D.K. Haze pollution, government governance and high-quality economic development. *Econ. Res. J.* **2018**, *36*, 20–33.
52. Qian, H.Z.; Tao, Y.Q.; Cao, S.W.; Cao, W. Theories and empirical evidence of China's digital finance development and economic growth. *J. Quant. Technol. Econ.* **2020**, *37*, 26–46.
53. Li, J.J.; Han, X. Financial Inclusion, Income Distribution, and Poverty Alleviation—Options for Policy Frameworks to Advance Efficiency and Equity. *J. Financ. Res.* **2019**, *465*, 129–148.

54. He, Z.Y.; Song, X.G. How the development of digital finance affects household consumption. *Financ. Trade Econ.* **2020**, *41*, 65–79.
55. Zhao, T.; Zhang, Z.; Liang, S.K. Digital Economy, Entrepreneurial Activity, and High-Quality Development: Empirical Evidence from Chinese Cities. *Manag. World* **2020**, *36*, 65–76.

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