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Digital Inclusive Finance and Carbon Emission Efficiency: Evidence from China's Economic Zones

Wei Jia [1], Zhihao Wang [1] and Lei Liu [2,*]

[1] School of Political Science and Public Administration, Qingdao University, Qingdao 266071, China; jiawei@qdu.edu.cn (W.J.); wangzhihao@qdu.edu.cn (Z.W.)
[2] School of Economics and Management, Dalian University of Technology, Dalian 116081, China
* Correspondence: ll15450176@mail.dlut.edu.cn

Abstract: In the current tide of technological revolution and industrial transformation, digitalization and greening have surfaced as two prominent trends, serving as the inherent requisites and impelling forces of new productive forces. Augmenting carbon emission efficiency is a crucial pathway for attaining green development. Digital inclusive finance, as an innovative financial paradigm, is a significant determinant influencing carbon emission efficiency and the progression of green development. By harnessing panel data from 108 cities within the Yangtze River Economic Belt spanning from 2011 to 2021, this study deploys the super-efficiency SBM model to gauge carbon emission efficiency. Additionally, it employs fixed effects and mediating mechanism models to empirically scrutinize the impact of digital inclusive finance on carbon emission efficiency within urban agglomerations in the Yangtze River Economic Belt. The study further probes its spatial effects through a spatial Durbin model. The research findings disclose that digital inclusive finance can substantially augment carbon emission efficiency in regional cities along the Yangtze River Economic Belt, manifesting notable regional correlations. This enhancement is accomplished by propelling industrial structure upgrades and augmenting scientific and technological capabilities. To enhance carbon emission efficiency in the Yangtze River Economic Belt, efforts should be centered around advancing digital inclusive finance, expediting industrial structural transformation, and fortifying scientific and technological development.

Keywords: new productive forces; digital inclusive finance; carbon emission efficiency; green development; spatial correlation

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1. Introduction

The rapid expansion of the global economy and the progress of industrialization in diverse countries have engendered a series of adverse ramifications. Among these, the greenhouse effect, instigated by emissions of gases such as carbon dioxide, poses a substantial menace to the sustainable development of the global economy. Consequently, countries across the globe are acutely fixated on the cultivation of a green economy, with the objective of enhancing carbon emission efficiency through the adoption of green industries, green social consumption, and other low-carbon production modalities [1]. For instance, the European Union is attempting to establish long-term green financial mechanisms to reduce carbon emissions, thereby maintaining a balance between social development and the environment. Similarly, the United States plans to vigorously develop clean energy and green-transform existing infrastructure to decrease greenhouse gas emissions.

In recent years, China has continuously focused on green development, particularly excelling in controlling greenhouse gas emissions compared to other countries. However, the effectiveness of these efforts remains limited. According to the International Energy Agency (IEA) report in 2023, China experienced an annual increase of 565 million tons in carbon dioxide emissions, the highest growth rate among all countries. To address the contradiction between "investment and effectiveness", China has attempted to improve carbon emission efficiency and develop a green economy through new quality production models [2,3]. New quality productivity centers on technological innovation, achieving industrial upgrades and development across multiple dimensions, including technology and institutions. Among these, inclusive digital financial inclusion is a critical area for enhancing carbon emission efficiency. Digital financial inclusion aims to leverage digital technologies such as the internet, data communications, big data, and artificial intelligence to reduce transaction costs and service barriers in the economic sector, thereby expanding the coverage of financial services. Supported by digital technologies, enterprises can more easily achieve green transformation and industrial upgrading. The costs for small and micro businesses to engage in capital investments and green consumption decrease, and the comprehensive utilization of social resources improves, thereby promoting the enhancement of societal carbon emission efficiency.

China's rapid and advanced development in digital financial inclusion provides a unique opportunity and foundation to explore the causal mechanisms between digital financial inclusion and carbon emissions. Furthermore, this research not only supports China's achievement of its dual carbon goals but also offers new pathways for other countries, including developed nations, to explore. However, current academic research in this field primarily focuses on the statistical relationships between the two, with the specific causal mechanisms remaining unclear. Additionally, there is a lack of attention to the carbon reduction benefits that digital financial inclusion offers to the government and various sectors of society.

Therefore, this study concentrates on two main issues: first, attempting to explain the pathways through which digital financial inclusion affects carbon efficiency; and second, examining the spatial dimensions of its impact, given the cross-regional nature of digital financial inclusion. The research is conducted following the below steps: first, reviewing relevant literature in the field and outlining existing research findings alongside the marginal contributions of this study; second, defining the research model and collecting data based on the research variables; third, utilizing the collected data to explore causal mechanisms and conduct spatial linkage analysis; fourth, discussing the regression results, summarizing the main findings, and proposing corresponding policy recommendations based on these findings; and fifth, addressing the unavoidable objective limitations encountered during the research process and suggesting subsequent solutions. By analyzing these core issues, this study aims to derive experiences that extend "beyond China", thereby providing support for the development of other regions around the world.

2. Literature Review

2.1. Carbon Emissions and Carbon Emission Efficiency

The dual-carbon challenge assumes a pivotal role in the context of urban green development. This research domain commonly encompasses fundamental concepts such as carbon emission intensity, total carbon emissions, and carbon emission efficiency. However, the definitions of concepts like carbon emission intensity and emission efficiency may give rise to misunderstandings and confusion. Research findings indicate that a city's carbon emission efficiency is not intrinsically correlated with its overall carbon emissions or intensity. In some of China's mega-cities, elevated carbon emissions often coexist with high carbon emission efficiency. Conversely, numerous heavy industrial and resource-based cities in China are characterized by significant pollution, high population density, and low efficiency. Certain small and medium-sized cities in China exhibit features of minimal overall carbon emissions, low intensity, and low efficiency. From a practical perspective, research on carbon emission efficiency is of greater significance than that on total emissions or intensity, as it more accurately captures the specific requirements and responses in emission reduction and efficiency across diverse urban typologies [4], thereby highlighting the necessity of its in-depth exploration.

In light of increasing domestic and international scrutiny regarding "dual carbon" objectives, numerous experts are concentrating on the spatiotemporal dynamics, assessment, quantification, and determinants of carbon emission efficiency. The assessment of carbon emission efficiency has transitioned from single-indicator evaluations to multiple composite-indicator assessments. The conventional assessment of carbon emission efficiency is often determined by the ratio of total carbon emissions to economic or energy metrics [5,6]. Measurement methods involving several factors encompass both parametric and non-parametric approaches [7]. In parametric approaches, researchers predominantly employ Stochastic Frontier Analysis (SFA) for efficiency assessment, especially for single-output and multi-input efficiency [8,9]; conversely, non-parametric methods typically utilize Data Envelopment Analysis (DEA). Nevertheless, due to the slack variable problem that reduces measurement precision, some improved models (SBM-desired, SBM-ML, and Super Efficiency SBM) have gradually emerged [10–12]. Carbon emission efficiency has been studied in relation to time and space using a variety of methods, such as spatial autocorrelation, K-means clustering, kernel density estimation, the Theil index, and spatial Markov chains. There are notable regional differences in China's carbon emission efficiency, which is improving over time [13,14]. The country also shows clear signs of spatial clustering, correlation, and spillover effects. Some research indicates that the main factors influencing carbon emission efficiency include the level of economic development, national policies and institutions, industrial structure, foreign direct investment, and urbanization level. Among these, technological innovation is considered a key factor in improving carbon emission efficiency and promoting the transition to a low-carbon economy [15,16].

2.2. Digital Inclusive Finance

With regard to the connotation of digital financial inclusion, the widespread adoption and deep integration of digital information technologies—including network technology, cloud technology, and intelligent computing—in the financial services industry has led to an increasingly close fusion of cutting-edge digital technologies and inclusive financial services. This has continuously expanded the conceptual scope of digital financial inclusion. The emergence and evolution of digitalized financial service methods have significantly enhanced the scope and penetration levels of inclusive financial services [17]. The implementation of digital technology has significantly lowered the costs of financial services and decreased their exclusivity, so fostering a new impetus for the advancement of inclusive finance [18,19]. The notion of digital financial inclusion was initially introduced at the G20 Hangzhou Summit in 2016. This concept includes a range of efforts aimed at advancing inclusive finance via digital financial services. It specifically denotes the utilization of digital technology to deliver a complete array of standardized financial services to populations that are either unable to access or deficient in financial services. The objective of these services is to address customer demands in a responsible and cost-effective manner while maintaining the sustainability of service providers [20]. Digital financial inclusion has attracted considerable scholarly interest, leading to more comprehensive discussions over its definition. Ozili posited that the objective of digital financial inclusion is to deliver fundamental financial services to demographics that are insufficiently covered by conventional financial institutions while guaranteeing that these services are agreeable to suppliers [21]. Dong Yufeng and Zhao Xiaoming posited in their research that digital financial inclusion signifies an advancement in inclusive financial services. Upon examining its service customization and operational framework, they observed that digital microfinance possesses both commercial and social attributes [22]. Du Minzhe and Huang Jie's research indicates that the advent of digital financial inclusion stems from the integration of financial technology innovation and inclusive services. Furthermore, the swift advancement of information technology has created new avenues for financial development, facilitating the widespread adoption of inclusive financial services, which exemplifies the pivotal role of technical innovation in propelling financial progress [23]. The fundamental importance of digital financial inclusion is in the utilization of digital technology to enhance the quality of inclusive services [24].

The evaluation of digital financial inclusion progress is considered an innovative framework that improves conventional financial services by integrating digital information technology with the advancement of inclusive finance, aiming to reduce financial service exclusivity. Thus, the evaluation of inclusive financial development is considered a complex concept. A measurement index system for inclusive finance has been established, encompassing three dimensions: accessibility, usefulness, and availability of banking services [25]. Beck established evaluation criteria for inclusive finance based on the accessibility of financial services, the effectiveness of financial product utilization, and the degree of geographical distribution [26]. The approaches for creating inclusive finance indicators are diverse, with researchers like Ma Yufei et al. analyzing the topic from macroeconomic, banking, and insurance perspectives [27]. Researchers such as Liu Yiwen and colleagues established an indicator system for inclusive finance comprising four dimensions: degree of popularization, service accessibility, application effectiveness, and cost affordability [28]. As digital information technology advances, it is crucial to evaluate the development of inclusive finance. Zou Wei and Ling Jianghuai emphasized the necessity of thoroughly integrating both traditional and digital elements of inclusive finance [29]. The evaluation of traditional inclusive finance primarily depends on the accessibility of financial services, the quality of those services, and their utilization rates. The evaluation of digital microfinance should focus on essential factors, such as the penetration of inter-net financial services, extent of utilization, and level of digital support. The progress of digital financial inclusion depends on the principles of digital and inclusive finance, integrating innovative digital financial metrics into the traditional inclusive finance indicator framework for assessment purposes [30]. In 2016, the Digital Finance Research Centre at Peking University formally released the "Peking University Digital Financial Inclusion Index", which underwent revision in 2019. This index has been revised to 2021, including 31 provinces, 337 prefecture-level cities, and 2800 counties in China [31].

2.3. Digital Inclusive Finance and Carbon Emission Efficiency

The interplay of finance, carbon emissions, and sustainable development has generated considerable scholarly discourse. Certain academics contend that the advancement of financial markets is essential for diminishing energy use and attaining societal carbon reduction objectives. In preliminary studies, Artur et al. indicated that financial development is a potent mechanism for mitigating environmental degradation, whereas financial liberalization acts as an effective means of decreasing carbon dioxide emissions [32]. Ouyang and other researchers formulated financial development indicators utilizing data on credit, insurance industry income, and stock market valuations. Their research indicated that financial development in a region markedly lowers energy use, thereby leading to a large reduction in carbon emissions [33]. He Jun et al. identified a negative link between the magnitude of loans extended by financial institutions, the financing scale of financial markets, and environmental degradation. Moreover, technological advancement serves a pivotal mediating function in this adverse association [34]. Conversely, some researchers contend that progress in finance seems to exacerbate carbon emissions. Proponents of this perspective assert that elements like technical advancement and foreign investment serve as intermediaries between financial progress and environmental damage [35]. Regional governments foster technological progress by increasing investments in research and development (R&D) and foreign direct investment (FDI). Although these initiatives catalyze swift technical advancement and promote wider economic and social development, they concurrently lead to the unavoidable consequence of heightened energy consumption and carbon emissions attributable to the rebound effect [36]. Furthermore, as the financial sector progresses, the increase in foreign investment may contribute to the "pollution haven" issue, adversely affecting initiatives to diminish carbon emissions.

The advancement of digital technologies has integrated traditional finance with contemporary technology, resulting in digital finance. Digital finance retains the fundamental attributes of traditional finance while including elements of immediacy and reduced costs. Scholars have progressively concentrated on digital money over time. Optimists assert that the continuous advancement of the digital economy is intricately connected to the decrease in carbon intensity, establishing a robust network of interrelations with entrepreneurship, technological innovation, industrial transformation, economic growth, and rural revitalization. This network is also sensitive to regional variation [37–39]. Empirical research utilizing urban data have revealed that the impact of digital finance on carbon emissions is not linear; rather, it demonstrates a double-threshold effect contingent upon its level of development [40]. The investigation of digital finance establishes a basis for additional inquiry into digital inclusive finance. Chien-Chiang Lee et al. [41] empirically established, utilizing panel data from 277 Chinese towns, that digital inclusive finance can markedly diminish carbon intensity via mechanisms such as industrial restructuring and advancements in green technology.

Finally, there is a lot of room for growth in the area of digital inclusive finance, even though many experts have already conducted extensive studies on the topic of digital finance and carbon emissions. Also, some academics claim that we no longer need to take into account the economic autonomy of specific cities because digital inclusive finance is applicable across regions thanks to digital technology. Nevertheless, this expectation does not align with reality due to the varying levels of digital inclusive finance development and sociocultural characteristics across regions. This study uses spatial econometric methods to analyze the spatial spillover effects between the two variables—digital inclusive finance and carbon emissions—to examine the interactive relationship between the two. These findings constitute the main contributions of the study: First, this study uses the model with the highest current accuracy (Super Efficiency SBM) to measure carbon emission efficiency. Secondly, it takes a look at the connection between digital inclusive finance and carbon emission efficiency from three angles: coverage depth, digitalization, and breadth of coverage. The underlying mechanisms are explained by looking at industry structure and technological advancement. Finally, using a spatial dynamic framework, this article examines the carbon emissions-related regional interconnections of cities and the geographical spillover benefits of digital inclusive financing.

3. Materials and Methods

3.1. Model Specification

3.1.1. Super-Efficiency SBM Model

The Data Envelopment Analysis (DEA) method represents a prominent research approach in academia, especially well-suited for handling matters related to "efficiency". This method provides an accurate reflection of efficiency levels in research objectives involving complex input-output relationships [42]. With further application, Tone identified the existence of slack variables within the model and developed a corresponding non-radial and non-oriented Slack-Based Measure (SBM) model, ultimately forming the super-efficiency SBM model. Compared to traditional DEA, the super-efficiency SBM model addresses the issue of slack variables and incorporates undesirable output variables [43]. Furthermore, traditional methods struggle to evaluate decision-making units (DMUs) with an efficiency value of 1. In contrast, the Super Efficiency SBM model can differentiate among such DMUs, ensuring more precise measurement results. In summary, this study employs the super-efficiency SBM model to estimate the carbon emission efficiency of Chinese cities. The specific formulas are as follows:

$$\min \rho = \frac{1 + \frac{1}{m}\sum_{i=1}^{m}\frac{S_i^-}{X_{ik}}}{1 - \frac{1}{v+u}\left(\sum_{r=1}^{v}\frac{S_r^+}{Y_{rk}} + \sum_{q=1}^{u}\frac{S_q^{o-}}{O_{qk}}\right)}$$

$$\begin{cases} \sum\limits_{\substack{j=1 \\ j \neq k}}^{n} \lambda_j X_{ij} - S_i^- \leq X_{ik},\ i = 1,\ 2\ldots,\ m \\ \sum\limits_{\substack{j=1 \\ j \neq k}}^{n} \lambda_j Y_{rj} + S_r^+ \geq Y_{rk},\ r = 1,\ 2\ldots,\ v \\ \sum\limits_{\substack{j=1 \\ j \neq k}}^{n} \lambda_j O_{qj} - S_q^{o-} \leq O_{qk},\ q = 1,\ 2\ldots,\ u \\ 1 - \frac{1}{v+u}\left(\sum_{r=1}^{v}\frac{S_r^+}{Y_{rk}} + \sum_{q=1}^{u}\frac{S_q^{0-}}{O_{qk}}\right)\rangle 0 \\ \lambda_j,\ S_i^-,\ S_r^+,\ S_q^{o-} \geq 0 \\ j = 1,\ 2\ldots n\ (j \neq k) \end{cases} \tag{1}$$

Among them, ρ represents the carbon emission efficiency of each DMU (Decision-Making Unit). If $\rho^* < 1$, it indicates that the carbon emission efficiency of the DMU in that period is in an inefficient state; and only when $\rho^* \geq 1$ can it be said that the carbon emission efficiency of the DMU has reached a strongly efficient state. m, v, and u, respectively, represent the number of variables for the three dimensions. X_{ij} represents the first input of the decision-making unit j, Y_{rj} represents the r-th desirable output of the decision-making unit j, and λ_j is the weight variable of the decision-making unit j. O_{kj} represents the k undesirable output of decision-making unit j. S_i^- and S_q^{o-} represent input redundancy and undesirable output redundancy while S_r^+ represents the shortage of desirable outputs. X_{ik}, Y_{rk}, Y_{qk} represent the vector values of inputs, desirable outputs, and undesirable outputs, respectively.

3.1.2. Two-Way Fixed Effects Model

The core focus of this study is the relationship between digital inclusive finance and carbon emission efficiency, necessitating control over potential influencing variables. Following preliminary data testing, this study employs a two-way fixed effects model, as shown in Equation (2):

$$CE_{it} = \alpha + \mu_i + \lambda_t + \beta DIF_{it} + \gamma X_{it} + \varepsilon_{it} \quad (2)$$

where CE represents carbon emission efficiency, DIF represents the level of digital inclusive finance development, α is the constant term, μ_i and λ_t represent the control effects for the province and time dimensions in this study, β and γ are the coefficients of the respective variables, and X represents control variables. The remaining variables are consistent with those mentioned earlier.

3.1.3. Mediation Effect Testing Model

Among the many methods available for testing mediation mechanisms, causal stepwise regression has become one of the most mainstream methods due to its clear structure, strong explanatory power, and high flexibility. However, when the mediator is included as a control variable in the baseline regression, issues such as covariance and error factors inevitably arise, potentially leading to misleading results. Therefore, following the method proposed by current articles, this study adopts a two-step approach.

$$\begin{cases} Y_i = cX_i + e_1 \\ M_i = aX_i + e_2 \end{cases} \quad (3)$$

where M_i represents the mediation variable.

3.2. Variable Selection

3.2.1. Dependent Variable

Carbon emission efficiency principally denotes the economic output or energy utilization efficiency corresponding to carbon emissions within a specific time frame. By drawing upon extant research, the evaluation index system for carbon emission efficiency encompasses three primary indicators and five secondary indicators (as presented in Table 1). The labor force is quantified by the total number of employed urban workers at the year-end. For each prefecture-level city, the capital stock is calculated using the methodology devised by Zhang Jun [44]. In consideration of the impact of price fluctuations on GDP and capital stock over different years, we adjust the data annually using a deflator to derive the real values corresponding to 2011. Total energy consumption is computed through a general method that converts energy consumption into standard coal equivalents, with the energy conversion factors being 1.33 kg of standard coal per cubic meter of natural gas, 1.71 kg of standard coal per kilogram of liquefied petroleum gas, 0.12 kg of standard coal per kilowatt-hour of electricity, and 0.03 kg of standard coal per megajoule of heat [45]. The data on urban carbon emissions are sourced from city statistical yearbooks and calculated in accordance with the IPCC inventory. A higher carbon emission efficiency implies a greater level of green development within the region. For enhanced visualization and analytical convenience, the carbon emission efficiency is multiplied by 100 for presentation purposes, thereby adjusting the data units without modifying the fundamental analytical outcomes.

Table 1. Indicator system for explanatory variables and explained variables.

	Primary Indicators	Secondary Indicators	Indicator Description
CEE	Input	Undesirable Output	Total number of urban employees at year-end
		Capital	Urban fixed capital stock
		Energy Consumption	Includes natural gas, liquefied petroleum gas, and social electricity consumption
	Desirable Output	GDP	Annual Gross Domestic Product of the city
	Undesirable Output	Total Carbon Emissions	Total carbon dioxide emissions of the city
DIF	Coverage	Account Coverage Rate	Number of Alipay Accounts per 10,000 People
		Payment Services	Proportion of Alipay Users with Bank Cards Bound Average Number of Bank Cards Bound per Alipay User Average Number of Payments per Person Average Payment Amount per Person Proportion of High-Frequency Active Users (50+ Annual Active Transactions) to Users with 1+ Active Transaction per Year
		Money Market Fund Services	Average Number of Yu'e Bao Purchases per Person Average Amount of Yu'e Bao Purchased per Person Number of Yu'e Bao Purchasers per 10,000 Alipay Users
	Usage Depth	Credit Services	Number of Users with Internet Consumer Loans per 10,000 Adult Alipay Users Average Number of Loan Transactions per Person Average Loan Amount per Person Number of Users with Internet Microbusiness Loans per 10,000 Adult Alipay Users Average Number of Loans per Microbusiness Owner Average Loan Amount per Microbusiness Owner
		Insurance Services	Number of Insured Users per 10,000 Alipay Users Average Number of Insurance Transactions per Person Average Insurance Amount per Person
		Investment Services	Number of Investment Participants per 10,000 Alipay Users Average Number of Investment Transactions per Person Average Investment Amount per Person
		Credit Services	Average Number of Credit Calls per Natural Person Number of Users Using Credit-Based Services per 10,000 Alipay Users
	Digitalization Level	Mobility	Proportion of Mobile Payment Transactions Proportion of Mobile Payment Amount
		Affordability	Average Loan Interest Rate for Microbusiness Owners Average Loan Interest Rate for Individuals
		Creditization	Proportion of Transactions Paid with Huabei (Installments) Proportion of Payment Amounts Paid with Huabei (Installments) Proportion of Transactions Using Zhima Credit (No Deposit) vs. All Deposit-Based Transactions Proportion of Amounts Paid Using Zhima Credit (No Deposit) vs. All Deposit-Based Transactions
		Convenience	Proportion of Transactions Paid Using QR Codes Proportion of Payment Amounts Paid Using QR Codes

Source: Compiled and calculated by the authors.

3.2.2. Explanatory Variable

In the existing literature on measuring digital inclusive finance, most studies restrict their research scope to a single region, meaning their indicator systems often fail to meet the needs of large-scale measurement. Among these efforts, Peking University was one of the first institutions to explore this domain, accumulating substantial research experience over time. When constructing its digital inclusive finance index, three principles were followed: first, the breadth and depth of digital financial services are of paramount importance; second, the selected indicators should allow for both longitudinal and cross-sectional comparability; and third, the index should be a comprehensive, multi-level, and diversified measure. Ultimately, the indicator system was constructed from three dimensions—coverage breadth, usage depth, and the digitalization level of inclusive finance. This comprehensive indicator framework can accommodate the varying requirements of digital inclusive finance across different regions, aligning with the relatively extensive scope of this study [46]. Accordingly, this study adopts these indicators as the basis for measuring the explanatory variables (see Table 1).

In the heterogeneous analysis part, this paper classifies the index into multiple dimensions, which are the scope of coverage, the depth of use, and the level of digitization.

3.2.3. Mechanism Variables

The ratio of regional tertiary industry to secondary industry is regarded as the proxy factor of industrial structure. Academic circles usually use the ratio of the expenditure on science and technology in the city to the expenditure on a local general public budget to measure the level of science and technology in this area.

3.2.4. Control Variables

Human Capital Level: This is represented as the proportion of the number of students enrolled in regular tertiary institutions relative to the total population at the end of the year. Human capital is a crucial factor that exerts an impact on carbon emission efficiency.

Fiscal pressure (public fiscal expenditure/public fiscal revenue) is directly related to the level of government funding allocated to environmental governance. The greater the fiscal pressure, the tighter the budget constraint on carbon emission reduction efforts, which in turn hinders urban carbon abatement.

Regional Openness Level: This is denoted by the actual amount of foreign investment. Urbanization Level: It is represented by the proportion of the urban population to the total population. Economic Development Level: It is quantified by the city's year-end Gross Domestic Product (GDP).

3.3. Data Sources

Compared to digital finance, digital inclusive finance demands higher levels of digitalization in a region, manifested in digital infrastructure, industrial, financial demand, and organizational transformation. Currently, China has seen some degree of development in digital inclusive finance, primarily in regions such as the Yangtze River Economic Belt and the eastern coastal areas. As a key strategic development region and economic front-runner, the Yangtze River Economic Belt plays a vital role in the development of digital inclusive finance and the upgrading of a green, low-carbon economy. The Yangtze River Economic Belt covers 11 provinces and municipalities along the Yangtze River, accounting for about half of China's total population and economic output. Therefore, selecting the Yangtze River Economic Belt as the research object provides a representative reflection of the current state of digital inclusive finance and carbon efficiency development in China.

The Yangtze River Economic Belt comprises 11 provinces and municipalities, including Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Guizhou, and Yunnan. The study uses data from 108 cities in the region, including both directly governed municipalities and prefecture-level cities. Additional primary data sources include the *China Urban Statistics Yearbook*, *China Urban and Rural Construction Statistics Yearbook*, *China Environmental Statistics Yearbook*, as well as national and provincial statistical yearbooks. Missing data values were supplemented using interpolation methods where necessary. Carbon emission efficiency data were calculated using MaxDEA9 software based on the original data. All results presented in tables and figures were generated using Stata17 software.

3.4. Descriptive Statistics

From the descriptive statistics of certain variables (Table 2), the overall mean of carbon emission efficiency is 77.3. Although the difference between the minimum and maximum values is approximately double, the relatively low standard deviation indicates small relative differences in carbon emission efficiency within the region. In terms of digital inclusive finance, the range is 338.44, with a relatively large standard deviation (74.47), reflecting both significant relative and absolute differences. This suggests that the development of digital inclusive finance is uneven across cities.

Table 2. Descriptive statistical results of some variables.

Variable Name	Mean	S.D.	Min	Max	Upstream Region	Middle Region	Downstream Region
Carbon Emission Efficiency	77.3	12.9	49.6	100.3	58.558	84.282	85.434
Digital Inclusive Finance	188.3	74.47	21.26	359.7	173.881	182.962	203.972
Fiscal Pressure	1.625	1.325	0.0963	10.40			
Foreign Investment Level	0.0205	0.0179	1.77×10^{-6}	0.135			
Economic Development Level	2.709×10^{7}	3.713×10^{7}	1.066×10^{6}	3.507×10^{8}			
Human Capital Level	0.0191	0.0243	1.50×10^{-5}	0.131			
Urbanization Level	0.551	0.130	0.181	0.896			
Industrial Structure	0.968	0.443	0.272	5.072			
Technological Level	0.0226	0.0195	0.00137	0.163			

Source: Compiled and calculated by the authors.

Additionally, this study calculates the statistical results of key variables for urban agglomerations in the upper, middle, and lower reaches of the Yangtze River. Both carbon emission efficiency and digital inclusive finance exhibit a spatial pattern of "gradual improvement from the upper to the lower reaches", which aligns with the overall development pattern of eastern, central, and western China. Furthermore, the comprehensive carbon emission efficiency of the upper-reach urban agglomerations is relatively low, with a notable gap compared to those in the middle and lower reaches.

4. Results

4.1. Baseline Regression

The content exhibited in Table 3 depicts the impact consequences of overall digital inclusive finance and its assorted dimensions. Columns (2), (3), (4), and (5) encompass the results obtained after incorporating control variables. Irrespective of whether control variables are included, the coefficient of digital inclusive finance remains positive and statistically significant, implying that DIF contributes to the enhancement of urban carbon emission efficiency and the advancement of a green economy. The results pertaining to fiscal pressure do not fulfill the significance criterion, suggesting that its direct impact on carbon emission efficiency might be relatively constrained. Regional openness and urbanization levels emerge as negative predictors of carbon emission efficiency, whereas local economic development levels tend to display a high degree of correlation with carbon emission efficiency.

Table 3. Baseline regression results.

Variable Name	(1)	(2)	(3)	(4)	(5)
Digital Inclusive Finance	0.051 *** (4.06)	0.037 *** (3.10)			
Coverage Breadth			0.017 * (1.66)		
Usage Depth				0.041 *** (4.05)	
Degree of Digitalization					0.013 *** (2.87)
Control Variables	NO	YES	YES	YES	YES
City Effects	YES	YES	YES	YES	YES
Time Effects	YES	YES	YES	YES	YES
R2	0.501	0.674	0.493	0.503	0.496

Note: ***, **, and * represent significance levels of 1%, 5%, and 10%, respectively, and the values in parentheses are robust standard errors clustered at the city level. Source: Compiled and calculated by the authors.

Furthermore, the regression results for the different dimensions of digital inclusive finance also show positive benefits. Among these, the depth of financial services usage has the largest effect on improving carbon emission efficiency, far exceeding both coverage breadth and digitization level. Overall, as the level of digital inclusive finance in a city increases, the carbon emission efficiency of that region also improves, with the depth of financial services usage having the greatest impact on the region's green development.

4.2. Mediation Mechanism Test

The changes in regional carbon emission efficiency are often highly coupled with shifts in industrial structure. In China and many other countries, industrial structures are gradually transitioning toward low-carbon, high-value-added industries, with traditional high-carbon-emission industries (e.g., coal, steel) being progressively phased out. At the same time, the industrial agglomeration effect enables more efficient resource allocation and productive interactions among emerging industries, thereby driving urban economies toward green and sustainable development. Moreover, the transformation of industrial structures is accompanied by technological advancements. Innovations in the energy sector—such as renewable energy, power transmission, and low-carbon materials—are key direct factors in reducing carbon emissions. In terms of carbon management, certain mature carbon conversion technologies can capture and store CO_2 and subsequently convert it into new materials or energy, significantly enhancing carbon emission efficiency.

Based on the above discussion, this study incorporates two variables—industrial structure and technological level—to analyze their roles in the research process, aiming to further strengthen the causal explanatory power of the model (Figure 1).

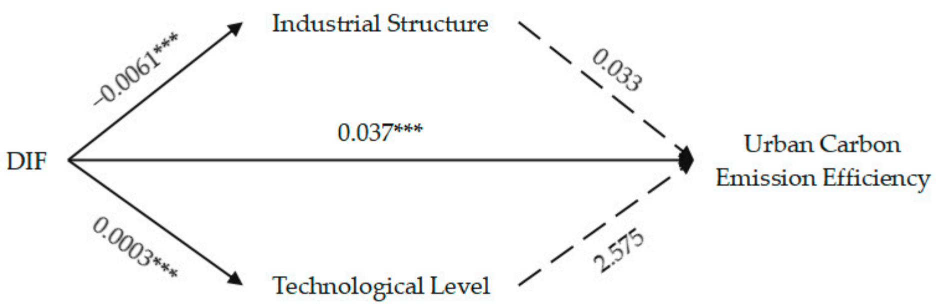

Figure 1. Mediation mechanism flowchart. Note: ***, **, and * represent significance levels of 1%, 5%, and 10%, respectively. Source: Compiled and calculated by the authors.

On one hand, digital inclusive finance serves as a positive predictor of urban carbon emission efficiency. On the other hand, industrial structure and technological level demonstrate certain mediating effects. Notably, industrial structure exerts an inhibitory effect, which contrasts with the direct effect.

4.3. Endogeneity Test

For the sake of the validity and reliability of the findings, this study addresses the potential endogeneity issues that may affect the above tests. We replaced the independent variable with the lagged data for digital inclusive finance by one and two periods and re-estimated the model. Table 4 displays the outcomes. Regression results are displayed in columns (1) and (2) using lagged digital inclusive finance data for one and two periods, respectively. In both cases, the positive effect of digital inclusive finance remains statistically significant. This finding backs up the hypothesis that digital inclusive finance contributes positively to better carbon emission efficiency while simultaneously reducing the impact of endogeneity on the estimation results. Applying this method strengthens the credibility of the original analysis results, providing more robust evidence of the correlation between enhancing environmental efficiency and digital inclusive finance. In summary, even after accounting for endogeneity concerns, the previous test results still hold, and digital inclusive finance continues to significantly affect carbon emission efficiency.

Table 4. Endogeneity test results.

Variable Name	(1)	(2)
One-period Lag of Digital Inclusive Finance	0.053 *** (3.56)	
Two-period Lag of Digital Inclusive Finance		0.063 *** (2.80)
Control Variables	YES	YES
City Effects	YES	YES
Time Effects	YES	YES
Observations	1080	972
R2	0.690	0.700

Note: ***, **, and * represent significance levels of 1%, 5%, and 10%, respectively, and the values in parentheses are robust standard errors clustered at the city level. Source: Compiled and calculated by the authors.

4.4. Further Research

4.4.1. Spatial Autocorrelation Test

Prior to delving into the geographical implications of digital inclusive finance's impact on carbon emission efficiency, we first need to confirm whether there is spatial autocorrelation among Yangtze River Economic Belt cities. That said, we employ the global Moran's I index to find out how these cities' carbon emission efficiency correlates spatially. As a measure of spatial autocorrelation, Moran's I can take on values between −1 (completely negative correlation) and +1 (completely positive correlation), with 0 indicating no spatial autocorrelation. In this study, a geographical distance matrix is used to replace the traditional adjacency matrix, as the geographical distance matrix incorporates actual spatial distances. This approach better reflects the natural spatial relationships and interaction effects between cities.

According to the analysis (Table 5), the Moran's I indices for efficiency in reducing carbon emissions in Yangtze River Economic Belt cities between 2011 and 2021 are all positive, fluctuating between 0.377 and 0.424, which suggests the carbon emission efficiency of these cities is positively correlated with one another. In other words, better carbon emission efficiency cities tend to have neighboring cities with higher efficiency as well.

Table 5. Moran's I of carbon emission efficiency.

Year	I	E (I)	Sd (I)	z	*p*
2011	0.422	−0.009	0.012	34.926	0.000
2012	0.417	−0.009	0.012	34.511	0.000
2013	0.416	−0.009	0.012	34.430	0.000
2014	0.412	−0.009	0.012	34.122	0.000
2015	0.414	−0.009	0.012	34.259	0.000
2016	0.377	−0.009	0.012	31.267	0.000
2017	0.384	−0.009	0.012	31.850	0.000
2018	0.416	−0.009	0.012	34.478	0.000
2019	0.421	−0.009	0.012	34.817	0.000
2020	0.411	−0.009	0.012	34.059	0.000
2021	0.424	−0.009	0.012	35.078	0.000

The Z-value measures the significance of Moran's I index by evaluating the difference between the observed spatial autocorrelation and a random spatial pattern. From 2011 to 2021, the Z-values range from 34.926 to 35.078, indicating that the observed spatial autocorrelation is highly significant, far exceeding the randomness threshold. The *p*-value tests the null hypothesis of no spatial autocorrelation. Here, we reject the null hypothesis in every case where the *p*-value is 0.000, confirming the significant spatial autocorrelation as an alternate hypothesis. This reinforces the findings from Moran's I and Z-values, emphasizing the strong positive spatial correlation. These data suggest that carbon emission efficiency in cities within the Yangtze River Economic Belt is not randomly distributed but significantly influenced by neighboring cities. This implies that carbon emission efficiency is interdependent among cities, showing a trend of increasing spatial correlation over time. Based on this, we can preliminarily infer the existence of spatial spillover effects in urban carbon emission efficiency. These findings provide crucial support for further investigating the spatial spillover effects between urban areas along the Yangtze River.

To enhance the visibility of the results, this study plotted Moran scatter plots (Figure 2). The plots for the two years exhibit a high degree of consistency, with approximately 98.15% of cities clustered in the first quadrant (H-H cluster) and the third quadrant (L-L cluster). This result confirms the positive spatial correlation among cities within the study region—cities adjacent to areas with high (or low) carbon emission efficiency also exhibit relatively high (or low) carbon emission efficiency. During the observation period, this spatial clustering effect remained highly stable.

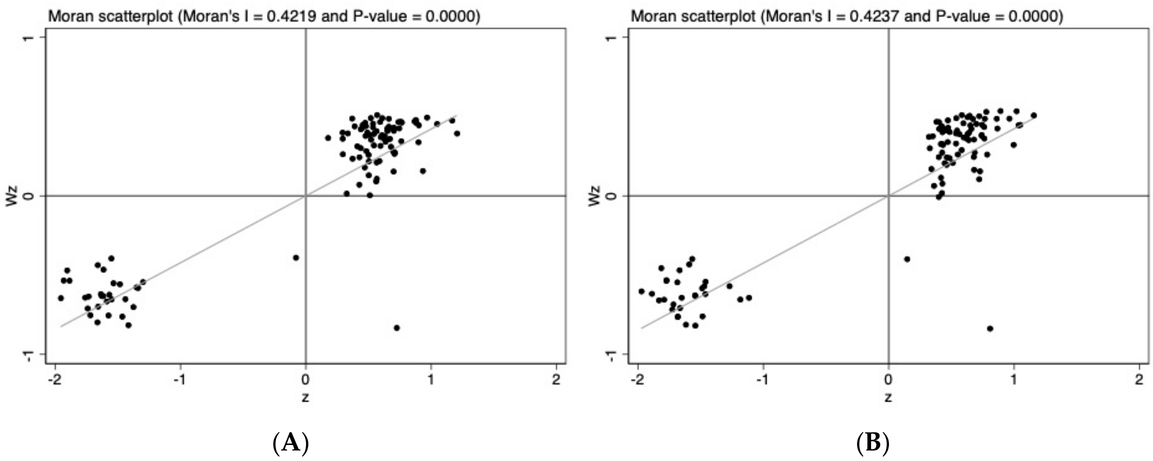

Figure 2. Local Moran scatter plot: (**A**) 2011; (**B**) 2021. Source: Compiled and calculated by the authors.

4.4.2. Selection of Spatial Econometric Model

On the basis of the above analysis, we have discovered that the degree of TE and CO_2 emission efficiency have an impressive correlation in urban areas. Based on these findings, the next phase of the study aims to further analyze the relation of DFI with CO_2 emissions using a spatial econometric model.

LM Test: The LM Test is a kind of measure for measuring the space relation in normal static panel regression. It consists of four types of tests: LM-Lag, Robust LM-Lag, and LM-Error and Robust LM-Error, as well as the LM-Error and Robust LM-Error tests. The results from these tests show that, for the sample data in this study, the null hypothesis was rejected, indicating that the sample data exhibit both spatial lag and spatial error autocorrelation effects. Therefore, this study should choose the spatial regression model.

Hausman Test: The null hypothesis of the Hausman test states that the random effects model is appropriate. The test statistic is 133.11, which meets the significance requirement. This leads to the rejection of the null hypothesis, indicating that the fixed effects model should be used.

LR Test: Spatial regression models include various types, and the LR test is employed in this study to optimize model selection (Table 6). This method typically performs likelihood ratio tests across different types of spatial models. The final results are 97.67 and 35.63, both of which pass the significance test. Therefore, the Spatial Durbin Model was selected for this study.

Table 6. Test results of various items.

	Direct Effect	***p***
LM Test Error	2111.557	0.000
Robust LM Test Error	1859.431	0.000
LM Test Lag	657.444	0.000
Robust LM Test Lag	405.318	0.000
Hausman	133.11	0.000
LR SAR	97.67	0.000
LR SEM	35.63	0.000

Source: Compiled and calculated by the authors.

4.4.3. Spatial Spillover Effect Decomposition

A series of preliminary tests indicate that the Spatial Durbin Model is the most suitable for analyzing spatial spillover effects. Additionally, this study employs the partial differentiation method to decompose the results, aiming to obtain more precise estimates of spatial spillover effects (Table 7).

Table 7. Decomposition of spatial effects in the spatial Durbin model.

Variable	**Direct Effect**	**Indirect Effect**	**Total Effect**
Digital Inclusive Finance	0.020 * (1.74)	0.230 *** (2.89)	0.250 *** (3.19)
Control Variables	Controlled	Controlled	Controlled

Note: ***, **, and * represent significance levels of 1%, 5%, and 10%, respectively. Values in parentheses are Z-values. Source: Compiled and calculated by the authors.

The results for the direct effects indicate positive benefits, showing that the development of digital inclusive finance brings significant carbon emission reduction benefits to cities, consistent with the earlier findings of this study. More importantly, a city's level of digital inclusive finance generates even greater green benefits for neighboring cities, with these spillover effects surpassing the localized benefits. Considering the results of the Local Moran Index and the realities of development, this phenomenon appears to be driven by industrial agglomeration and the flow of production factors between cities. The coefficient of the total effect, which meets the significance requirement, further confirms the existence of both types of benefits. The findings of this study indicate that when formulating policies that are pertinent to the issue at hand, economic, financial, and social factors should be taken into consideration in a comprehensive manner in order to produce an overall enhancement of the effectiveness of carbon emissions.

5. Discussion

5.1. Digital Inclusive Finance and the Improvement of Carbon Emission Efficiency

Current research indicates that digital inclusive finance, by integrating the latest technological tools, including cloud computing, big data, and network technologies, endeavors to furnish convenient and efficient financial services to a broader spectrum of users. Through the assimilation of digital technologies such as informatization and intelligence, financial services have evolved from traditional models to more efficient ones. Propelled by digital inclusive finance, technology enterprises can harness digital technologies to expand the frontiers of financial services, reduce the difficulty of accessing services, and augment financing efficiency by enhancing information sharing and alleviating the risks associated with information asymmetry. This, in turn, channels more capital towards high-tech and strategic emerging industries [47]. Moreover, with the characteristics of high marginal efficiency, wide dissemination, and low cost, digital inclusive finance, steered by green technology innovation, spurs enterprises to actively pursue industrial and technological upgrades, thereby fostering the progression towards a long-term environmentally friendly economy [48]. The cross-border communication and data-sharing capabilities of digital technology lay the groundwork for direct linkages between suppliers and demanders, facilitating continuous reform of financial services and effectively enhancing the efficiency of social resource allocation.

The results of this study also confirm the favorable effects of digitally inclusive financing on the effectiveness of carbon emission reduction efforts. However, this positive effect is not a simple linear relationship [49]. Specifically, the proliferation of digital inclusive finance contributes to improving carbon emission efficiency, but more importantly, the level of digitalization of financial activities and the level of use of financial services are more important in enhancing environmental efficiency. This may be because deeper usage implies that businesses and individuals can more effectively leverage digital financial services in their economic activities, optimizing resource allocation and promoting the implementation of energy-efficient technology. Concurrently, the greater the level of digitization reflects the extent to which financial technologies penetrate economic activities. These technologies improve transaction efficiency, reduce energy consumption, and support green financial product innovation, further enhancing carbon emission efficiency. Although there is a positive correlation between coverage breadth and carbon emission efficiency, its relatively smaller effect may indicate that merely increasing financial service coverage, without improving the level of digitalization and usage, has a limited impact on enhancing carbon emission efficiency.

Additionally, various urban development factors also influence the green benefits of digital inclusive finance. Highly open cities often become hubs for high-energy-consuming and high-polluting industries, which directly exacerbates local carbon emissions. Furthermore, industrial agglomeration is accompanied by population clustering, creating higher demands on local urbanization levels. However, the negative impact of urbanization levels indicates that during this process, carbon emission efficiency is likely to decline due to increasing energy demands, highlighting the contradictory relationship between urbanization management and carbon emission efficiency. From a macro perspective, the current economic development of cities largely relies on technological progress. The advancement of technology may be the key to addressing these issues. Accordingly, the data suggests that higher levels of urban economic development can mitigate the negative effects of regional openness and urbanization levels.

5.2. The Mediating Pathways of Industrial Structure and Technological Advancement

Figure 1 illustrates the routes that mediate industrial structure and technological advancement. The development of financial services performs an important function in promoting industrial structural upgrades. The financial system, through capital allocation, optimization of the business environment, and support for industrial progress, deeply influences resource distribution and industrial layout in the economy [50]. Digital inclusive finance, with its efficient data processing capabilities, can quickly identify high-efficiency, environmentally friendlysectors industrial sectors, directing capital to industries with higher technological content and driving industrial structural optimization [51]. This system encourages companies to upgrade production efficiency and lessen energy consumption [52]. The results of the mediation mechanism test reveal a correlation between the structure of industries and digital inclusive finance that is negative, potentially reflecting that inclusive digital finance has pushed the upgrading of certain industries that use a lot of energy, thus influencing the enhancement of carbon efficiency. This confirms that the key intermediary in this process is the structure of the industrial sector.

As an innovative component of the financial system, digital inclusive finance expands the boundaries of traditional financial services. With the help of digital tools like cloud computing and big data, it reduces financing barriers, especially for enterprises ranging from small to medium-sized and innovative technology companies, stimulating corporate innovation and techno-logical advancement [53]. The transformation of financial models not only reshapes the industrial ecosystem but also influences consumer behavior. Innovations in payment technologies drive upgrades in consumption patterns, further promoting continuous industrial improvements [54]. Additionally, digital inclusive finance reduces information asymmetry through big data technology, increases corporate transparency, and assists governments in effectively regulating polluting and energy-intensive businesses, reducing the cost of environmental supervision. These measures help encourage enterprises to develop green technologies and advance a more robust low-carbon economy. In other words, DIF plays a crucial role in enhancing carbon emission efficiency through two key dimensions: technological innovation and the application of new technologies.

5.3. The Spatial Correlation Between Digital Inclusive Finance and Carbon Emission Efficiency

Currently, some scholars have begun to explore the environmental benefits of digital inclusive finance. These studies primarily focus on outcome variables such as urban green economic efficiency [55] and carbon emission intensity [56], with findings that are largely consistent with those of this study. According to the direct effect's findings, the development of digital inclusive finance has a significant positive impact on local carbon emission efficiency, and the magnitude of this effect is quite near the calculated coefficient obtained using a standard fixed-effects model. Therefore, it appears that digital inclusive finance is a key factor propelling efficiency gains in local carbon emissions and that enhancing financial inclusivity can directly promote environmental improvement and energy efficiency. Furthermore, the logarithm of the control variable, the stage of development of each region, shows a significant positive direct effect, indicating that Cities exhibiting elevated economic development are more inclined to invest in efficient energy and environmental technologies, consequently enhancing carbon emission efficiency.

From the perspective of indirect effects, the inclusiveness of digital finance facilitates the diffusion of environmental investments and green technological innovations, fostering a pattern of production factor agglomeration that generates positive spillover environmental benefits [57]. Coupled with the positive spatial correlation between cities, if different cities continue to maintain the flow of production factors and the development of digital inclusive finance, it will significantly improve their environmental conditions and establish a sustainable positive feedback network. Moreover, these positive environmental benefits are likely to accumulate over time, amplifying their impact.

6. Conclusions and Recommendations

6.1. Conclusions

Based on the panel data of 108 cities in the Yangtze River Economic Belt, this research penetrates deeper into the effects of digital inclusive finance and the correlation between carbon emission efficiency in different regions. The key findings are as follows: (1) Digital inclusive finance is a positive predictor of urban carbon emission efficiency, chiefly owing to the depth of financial service utilization, which magnifies its impact. (2) A connection between digitally inclusive finance and carbon emission efficiency can be established through industrial structural upgrading. Digital inclusive finance indirectly augments carbon emission efficiency by promoting industrial transformation and upgrading. The interdependence between financial innovation and industrial development markedly influences environmental efficiency. (3) Digital inclusive finance propels carbon emission efficiency by advancing technological development. When promoting green urban development, the latent role of technological innovation in enhancing environmental efficiency should be recognized. (4) A positive spatial correlation exists between carbon emission efficiency in geographically adjacent cities. Moreover, urban carbon emission efficiency depends not only on the progress of local digital inclusive finance but also on the spatial spillover effect of digital inclusive finance from adjacent cities, which exceeds the direct effect.

Numerous scholars have examined digital financial inclusion from various perspectives. However, as an emerging economic form, there remains significant untapped potential, such as the environmental benefits of digital financial inclusion. It is undeniable that some researchers have focused on this field, but unfortunately, their studies are often limited to "point-to-point" analyses, primarily addressing how digital financial inclusion impacts environmental outcomes. This study systematically links digital financial inclusion with carbon emission efficiency, uncovering the mediating mechanisms of industry and technology, thereby enriching the theoretical foundations of environmental economics. Additionally, we introduced spatial linkage as a factor in the research process, expanding the application of regional economics to environmental studies and providing empirical evidence for the integrated development of theories across different fields in the future.

Furthermore, the urban agglomerations within China's Yangtze River Economic Belt encompass developed cities, newly developed cities, developing cities, and impoverished cities, offering important practical guidance for managers and financial institutions in various types of cities. At the same time, the results obtained from these urban clusters can, to some extent, reflect global developmental trends. For developing countries, once they have a certain foundation, developing digital financial inclusion can enhance local carbon emission efficiency. Furthermore, developed countries can leverage the digital economic cycle system between industry and finance to amplify the impact of digital technologies on economic growth, thereby improving carbon emission efficiency. Maintaining appropriate flows of production factors between different countries will also help realize the positive environmental benefits of digital financial inclusion.

6.2. Recommendations

Based on the aforementioned conclusions, the development of digital financial inclusion plays a crucial role in reducing carbon emissions and fostering a green economy.

Governments and markets must fully leverage the amplifying effect of digital technologies in economic development by constructing a digital ecological cycle system centered on "industry + finance". This involves steadily promoting the intelligent and digital upgrading of the financial industry and directing more funds toward high-tech and high value-added green emerging industries. In this process, financial service institutions should prioritize technological innovation as the core driving force when expanding investments in green financial products and services. They should promote the integration of information technologies such as artificial intelligence with financial services and enhance environmental risk management capabilities through tools like big data simulations.

Governments should clearly define industrial development plans, identify key green industry sectors, and implement targeted support policies to create a favorable innovation environment for high-tech and strategic emerging industries. Concurrently, they should deepen market reforms to optimize the financing environment, simplify the financing challenges for green projects and technologies, and establish a comprehensive venture capital mechanism to support the development of innovative enterprises. This approach will promote the deep integration of capital markets with the real economy, further facilitating the growth of green industries.

7. Future Prospects

It is important to note that the relationship between digital financial inclusion and carbon emission efficiency is often complex, involving numerous unobservable mediating variables that traditional econometric methods are unable to adequately address. During data collection for this study, an excessively long time span resulted in missing indicators and data sources, while inconsistent statistical standards led to collected data that could not fully meet the research requirements. Due to these limitations, the mediating paths of industry and technology selected in this study do not fully capture the complete and intricate relationship between digital financial inclusion and carbon emission efficiency. However, the gradual maturation of machine learning methods based on big data provides technical support to address this issue. Numerous techniques, such as decision trees, ensemble learning, and double machine learning, have demonstrated effectiveness in mitigating the impact of unobservable variables. Consequently, big data and new methodologies represent important directions for conducting in-depth analyses of the relationship between digital financial inclusion and carbon efficiency.

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