

Study on the Group Impact of Digital Financial Development on Carbon Emission Reduction Effect

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Abstract: Significant socioeconomic changes are represented by carbon peaking and carbon neutrality, with digital finance being essential to improving the efficiency of carbon emissions. This study uses panel data from 30 Chinese provinces from 2011 to 2022 to create a weighted SBM-DEA model for evaluating carbon emission efficiency. Using the dynamic QCA method, it further investigates optimization paths taking into account the external environment, development stages, and digital finance. The findings show that digital banking improves carbon emission efficiency in every way. Notably, there is a significant amount of integration between digital finance, scientific and technology innovation, and environmental legislation. Additionally, even though the need for conditional variables shows a growing trend, the intergroup consistency distance stays below 0.2. To increase carbon emission efficiency, three key categories can be efficiently optimized: high-quality digital finance-led, digital innovation-driven, and digital finance-innovation synergistic.

Keywords: Digital finance, Carbon emission reduction efficiency, Weighted SBM-DEA model, Dynamic QCA analysis.

1. Introduction

General Secretary Xi Jinping announced for the first time in September 2020 that "carbon dioxide emissions will strive to peak by 2030, and strive to achieve carbon neutrality by 2060", and the 20th Party Congress underlined the necessity of advancing carbon peaking and carbon neutrality in a proactive and steady manner. The "dual-carbon" goal plan indicates that China's green development has advanced to a new level, and "carbon reduction" is not only the general grasp of future ecological environmental protection work, but also the general orientation of economic development. With the advent of the information revolution, traditional finance and information technology are deeply integrated. Digital money is more convenient and inclusive than traditional finance, and research by Tamazian et al., Salahuddin et al., and Shahbaz et al. has demonstrated that financial development helps to improve the environment. Thus, more research into the precise function of digital banking in raising carbon emission efficiency is crucial. This paper thoroughly examines the impact of digital inclusive finance on carbon emission efficiency from the segmentation dimension of digital finance. With the aid of the group effect theory, it delves deeply into the effect of increasing the efficiency of carbon emission efficiency. Previous research primarily focuses on the relationship between digital finance and carbon emissions, with fewer studies focusing on digital finance and carbon emission efficiency. These studies also focus on the impact of scientific and technological innovation, environmental regulation, and other single factors on carbon emissions, we deeply investigate the internal conduction mechanism of improving carbon emission efficiency. A study of 30 provincial-level panel data in China from 2011 to 2022 is conducted to summarize the multifaceted impact paths of digital finance to enhance carbon emission efficiency, so as to enrich its theory and methodology.

2. Review of Research Perspectives

Carbon emissions serve as a negative output indicator for measuring carbon emission efficiency. Understanding the influencing factors is essential, particularly financial development, scientific and technological innovation, environmental regulation, and government intervention. The existing literature contains limited studies examining the factors influencing carbon emission efficiency, predominantly focusing on external and developmental factors.

Regarding external factors, Zhao Xiaochun et al. indicate that government intervention negatively affects carbon emission efficiency while positively influencing neighboring regions. According to Zhang Yabin et al., inconsistencies brought on by overzealous government involvement impede advancements in carbon emission efficiency. Wang Dong claims that environmental restrictions drastically lower carbon emission efficiency, while Jiang Sanliang finds a U-shaped and heterogeneous link between environmental regulation and carbon emission efficiency.

Regarding development levels, Li Deshan et al. suggest that advancements in R&D technology can effectively enhance carbon emission efficiency. They also find that financial development follows a positive U-shaped relationship with carbon emission efficiency. Similarly, Sun Jingbing posits that improvements in scientific and Innovation in technology has the potential to greatly increase carbon emission efficiency. At the moment, scholarly research frequently highlights how digital finance affects carbon emissions, with less attention paid to how it affects carbon emissions efficiency. Early research focused on the connection between environmental effect and economic growth, and the environmental Kuznets curve frequently took traditional financial development into account.

The current literature categorizes studies on the relationship between finance and the environment into three primary perspectives: finance improves the environment,

finance deteriorates the environment, and a non-linear relationship exists between the two. With the rapid advancement of the economy and the Internet, digital finance has become more inclusive and accessible than traditional finance. Financial institutions can leverage advanced technologies, including big data, cloud computing, and distributed ledger technology, to convert dispersed funds into effective supply, offer adequate credit to enterprises, and optimize financial management. Digital technologies facilitate offline financial transactions and enhance the management of interbank financial resources. The inclusivity of digital finance lowers financial service costs, offers additional financing channels for disadvantaged groups, alleviates funding challenges for private enterprises and small businesses, and improves overall enterprise productivity. In the research regarding the impact of digital finance on carbon emission efficiency, scholars generally concur that digital finance significantly enhances efficiency, with scientific and technological innovation, economic growth, and industrial transformation acting as key intermediary mechanisms. Digital inclusive financing increases carbon emission efficiency by lowering agricultural carbon emission intensity and raising the degree of socialized services in agricultural production, according to research by Shen Yun from an agricultural perspective, and deepening integration within the agricultural industry.

Although there is a fair amount of research on the topic of digital finance and carbon emissions, there are not many studies that really examine how efficient carbon emissions are in connection with digital finance. There are notable gaps in the investigation of digital finance's effect on carbon emission efficiency because existing research mostly looks at the relationship between digital finance and carbon emissions. First, most research focuses on overall digital finance indicators, neglecting the specific impacts of its sub-dimensions, which hampers understanding of digital finance's direct influence on carbon emission efficiency. Second, current studies often emphasize intermediary roles, utilizing linear regression to derive empirical attributions based on key factors such as environmental regulation, government intervention, and scientific innovation, thus overlooking the multifaceted interaction pathways of digital finance.

3. Theoretical Analysis

3.1. The Direct Effect on Carbon Emission Efficiency of The Divided Aspects of Digital Finance

Currently, digital technology is advancing the innovative practices of financial and monetary digitization in China, enhancing applications in areas such as payment, credit, and insurance. Consequently, digital finance is transforming the structure and delivery of traditional financial services. Three dimensions of digital finance are identified by Guo Feng et al.'s digital financial inclusion index: degree of digitization, depth of use, and breadth of coverage. Payment, insurance, and credit are the three most representative indicators of digital finance and should be included in this study. Consequently, the impact of digital finance on carbon emission efficiency can be analyzed in the following aspects:

Regarding the breadth of coverage, Bernanke (1999) suggests that, according to the financial gas pedal principle, digital finance alleviates the financing difficulties faced by the real economy, thereby confirming that financing

constraints significantly impact economic growth. Financial institutions can overcome geographical limitations associated with traditional financing by utilizing digital platforms to select enterprises. This enables the elimination of high energy-consuming and polluting businesses, while guiding fund flows toward environmentally friendly enterprises, thereby fostering a green ecosystem focused on optimal fund allocation and management.

Concerning depth of use, Sarma and Pais (2011) found that digital technologies in digital finance effectively extract valuable information from big data streams, optimizing the financial system and lowering costs. Creating online money fund services can increase market reach, help carbon trading pilots succeed, improve the inclusivity of carbon financial products in the carbon trading market, and internalize the externalities related to reducing carbon emissions.

With respect to the degree of digitization, digital finance expands information retrieval capabilities and alters data processing methods, enabling more effective risk identification and prevention. Digital finance platforms enable enterprises to manage external transactions and internal costs, generating visualized data that assists in optimal decision-making and profit maximization in alignment with government-mandated energy-saving and emission reduction policies. The following theories are put out in this study in light of the aforementioned analysis:

H1: The segmented dimensions of digital finance enhance carbon efficiency.

3.2. Multiple Pathway Impacts of Digital Finance on Carbon Efficiency

Scientific and technological innovation effectively intercepts pollution and reduces emissions. Research and development in green technology by enterprises can optimize their structures and integrate resource allocation, ultimately improving carbon emission efficiency. Because digital finance is inclusive, it can offer crucial financial support for small and medium-sized businesses' (SMEs) scientific and technology R&D and innovation efforts. This change greatly improves financial services' ability to support the actual economy in addition to facilitating the financial industry's transition from virtualization to materialization (Xue Ying and Hu Jian, 2020). Big data and cloud computing are two examples of technologies that can search, evaluate, and decide based on consumer consumption data., aiding enterprises in making informed decisions regarding innovation direction, potential, and paths. This transition promotes a shift from experience-driven to data-driven innovation, enhancing the success rate of technological research and development and the ability to translate R&D results into practice. Furthermore, a developed level of innovation can enhance the sophistication of digital financial platforms and bolster their capabilities. Scientific and technological innovation has given rise to a new type of financial institutions, significantly optimizing the financial structure. Enterprises serve as the "cells" of the industrial economy, and their "green" technological innovations can advance macro-level "green" technological progress, which in turn facilitates carbon emissions reduction. Consequently, this paper proposes the following hypotheses:

H2: The grouping of digital finance and STI can improve carbon efficiency.

Environmental regulation can be classified into two types: formal and informal. Formal regulation involves official

policies or guidelines that effectively reduce pollution emissions, while informal regulation encompasses voluntary public participation in environmental protection activities, fostering societal energy savings and emissions reductions (Jiang Sanliang, 2022). The integration of digital finance allows for the retrieval, categorization, and calculation of corporate information, delivering extensive environmental data to official departments, reducing information retrieval costs, and enabling more precise control over heavy industrial enterprises. Wang Dong comes to the conclusion that environmental regulation substantially reduces carbon emission efficiency, while Jiang Sanliang sees a "U"-shaped and variable link between environmental regulation and carbon emission efficiency. Thus, the following theories are put out in this paper:

H3: The grouping of digital finance and environmental regulation does not enhance carbon efficiency.

Government intervention aimed at energy conservation and emissions reduction must occur at an appropriate threshold. For instance, by introducing market mechanisms like carbon emission permits and trading systems, the government can effectively regulate regional carbon emissions. This market-based intervention strategy offers necessary incentives for regional decarbonization (Wang Bo et al., 2020). Factor mismatches stemming from excessive resource allocation and land concessions not only diminish carbon emission efficiency but also exacerbate regional developmental imbalances. Digital finance can invigorate the carbon trading market, while the impacts of government interventions, such as resource allocation, require further investigation. Consequently, this paper proposes the following hypotheses:

H4: The interaction between digital finance and government intervention does not enhance carbon efficiency.

Existing studies indicate a positive "U"-shaped relationship between financial development and carbon emission efficiency, suggesting that financial development can enhance carbon emission efficiency over time (Chen Bi-Qiong, 2014; Li Deshan et al., 2018). Traditional finance encountered challenges related to credit mismatches and inefficient fund allocation in its early stages. However, in recent years, digital finance has significantly developed in some regions, fully realizing its advantages. This effectively eliminates information barriers, enhances capital efficiency, and facilitates the widespread application of green credit, subsequently improving carbon emission efficiency. Consequently, this paper proposes the following hypotheses:

H5: The grouping of digital finance and financial development can improve carbon efficiency.

At the moment, China's digital innovation in monetary and financial sectors like payment, credit, and insurance is constantly driven and supported by digital technologies like big data, artificial intelligence, and blockchain. Traditional financial service forms are changing as a result of the growing depth of application in fields like investing. Carbon emission efficiency is also impacted by the entry of digital finance into the financial and economic spheres through particular channels. Few studies look at the overall effects of digital finance and the interconnections among these elements on carbon emission efficiency, despite the fact that researchers have used econometric approaches to confirm the significance of several influencing factors. From a long-term standpoint, digital finance is developing slowly. Investigating if digital finance platforms need to work with scientific innovation is vital, environmental regulation, government

intervention, and other mechanisms to effectively influence carbon emission efficiency, particularly during their maturation phase. From a horizontal standpoint, there is disparity in the growth of digital finance between the eastern, central, and western areas. The literature now in publication generally agrees that the eastern region has developed more quickly than the middle and western regions. More research is necessary to determine whether the early-developed eastern region and the more recent central and western regions have comparable and consistent levels of digital financial development. Therefore, the purpose of this article is to investigate the impact and efficacy of digital finance as well as the many elements that influence the improvement of carbon emission efficiency. In order to examine panel data and find efficient ways to increase efficiency, this entails elucidating pertinent elements and using dynamic QCA methodology.

This research divides them into two groups based on the examination of pertinent influencing elements affecting carbon emission efficiency: external environment and level of development. It also delineates digital finance according to its secondary indicators, treating them as conditional variables. The external environment encompasses environmental regulation and government intervention. The level of development includes financial development and regional innovation levels. Digital finance is subdivided into the breadth of coverage, depth of use, and degree of digitization, as well as payment, insurance, and credit, which serve as outcome variables. This paper conducts a grouping analysis of the ten subcategories across the three categories to enhance carbon emission efficiency, investigating how each factor grouping can effectively improve efficiency.

4. Research Design

4.1. Research Methodology

4.1.1. Data Envelopment Analysis

Regarding research methods for carbon emission efficiency, it is defined from an economic perspective and primarily categorized into single-factor and total-factor carbon emission efficiency. The carbon emission efficiency index based on GDP tends to favor developed countries, as their total GDP is generally higher, while the index based on energy consumption tends to favor developing countries. In terms of measurement methods, scholars typically employ the Data Envelopment Analysis (DEA) approach. From an axiomatic perspective, the DEA radial measurement method demonstrates certain ideal mathematical characteristics and is widely practiced. Because this method does not require consideration of data correlation or the independence of random variables, it can yield optimal results with fewer parameters. However, the radial method may overstate efficiency values when non-zero slack exists. By transforming the problem into a linear constrained optimization model, findings from existing literature on optimal solutions can be utilized to establish new objective parameters. Therefore, the weighted SBM-DEA method is employed to address the shortcomings of the traditional directional distance function.

This study builds a production possibility set with a single wanted output and a single non-desired outcome, taking into account China's status as a developing nation and the existence of non-zero slack. Using capital stock, labor, and energy consumption as inputs, it assesses the carbon emission

efficiency of 30 provinces, autonomous regions, and municipalities—with Tibet excluded—with real GDP as the desired output and carbon dioxide emissions as the undesirable output.

Three input variables, one desired output variable, and one non-desired output variable make up the chosen indicators. The non-radial directional distance function is used to measure the carbon emission efficiency; a higher value denotes a higher carbon emission efficiency. A city or province is said to be at its technological frontier when its carbon emission efficiency is equal to 1, which indicates that it is functioning at maximum efficiency.

4.1.2. Dynamic QCA

Most existing studies are limited to cross-sectional data, with few exploring the effects of longitudinal time on grouping. Digital financial development evolves annually, making cross-sectional data analysis insufficient to fully elucidate its impact on carbon emission efficiency. Therefore, this paper employs R software and the dynamic QCA method to overcome the limitations of panel data and traditional QCA approaches, examining the relationship of grouping within longitudinal time effects.

Ragin (2008) proposes a general measure of set-theoretic consistency or inclusion between two sets:

$$Consistency(X_i \leq Y_i) = \frac{\sum_{i=1}^N \min(X_i, Y_i)}{\sum_{i=1}^N X_i} \quad (1)$$

The degree of affiliation between individual I and set X is represented by X, while the degree of affiliation between individual I and set Y is indicated by Y. Three different kinds of constancy are introduced by the passage of time, though. We can calculate the overall panel consistency for all $i = 1, 2, \dots, N$ and $t = 1, 2, \dots, T$, if we define i as the number of cross-sectional observations and t as the number of cycles in the panel data. This kind of consistency is known by T. Garcia as Pooled Consistency, or POCONS, and is described as follows:

$$Pooled\ Consistency(X_{it} \leq Y_{it}) = \frac{\sum_{i=1}^N \sum_{t=1}^T \min(X_{it}, Y_{it})}{\sum_{i=1}^N \sum_{t=1}^T X_{it}} \quad (2)$$

where X_{it} is the affiliation of individual i in the set X at time t , and Y_{it} is its affiliation in the set Y. According to Ragin, "merged consistency" refers to the overall consistency seen in the sample when temporal and individual influences are ignored. This is the same as "merging all cross-sectional consistencies." Next, the panel's consistency is calculated for each year t :

$$Between\ Consistency(X_{it} \leq Y_{it}) = \frac{\sum_{i=1}^N \min(X_{it}, Y_{it})}{\sum_{i=1}^N X_{it}} \quad (3)$$

A group's cross-sectional consistency for each year t is measured by Between Consistency (BECONS). Ragin refers to BECONS, the most widely used consistency metric in the literature, as just "consistency" in his set theory study.

Lastly, the postulated subset linkages between X_{it} and Y_{it} can also be measured over time to see if they hold true across cases.

$$Within\ Consistency(X_{it} \leq Y_{it}) = \frac{\sum_{t=1}^T \min(X_{it}, Y_{it})}{\sum_{t=1}^T X_{it}} \quad (4)$$

for each $i=1, \dots, N$.

The longitudinal consistency of set-subset connections for every i in the panel across time is measured by Within Consistency (WICONS). Put differently, WICONS evaluates the constancy of set-subset relationships across time for each unique case in the sample. There are T unique BECONS, N unique WICONS, and one POCONS in every real panel dataset. To obtain a thorough grasp of the set-subset linkages between causal conditions and outcomes, it is crucial to take into account BECONS, WICONS, and POCONS, as they can differ in empirical investigations. In order to analyze the time versus cross-sectional impacts within a case, Garcia highlights the importance of thoroughly examining intra- and inter-group distances.

The following are the consistent Euclidean distances calculated within and between groups:

$$BECONS\ Distance = d(BECONS, POCONS) = \sqrt{\sum_{t=1}^T \left(\frac{BECONS_t}{\sum_{t=1}^T BECONS_t} - \frac{1}{T} \right)^2} \quad (5)$$

$$WICONS\ Distance = d(WICONS, POCONS) = \sqrt{\sum_{i=1}^N \left(\frac{WICONS_i}{\sum_{i=1}^N WICONS_i} - \frac{1}{N} \right)^2} \quad (6)$$

Here are the improved consistency adjustment distances:

$$BECONS\ adjusted\ distance = \frac{BECONS\ distance}{\sqrt{\frac{n}{n^2 + 3n + 2}}} \quad (7)$$

$$WICONS\ adjusted\ distance = \frac{WICONS\ distance}{\sqrt{\frac{n}{n^2 + 3n + 2}}} \quad (8)$$

Panels of any size can easily use the modified distance. When applied to actual datasets, the adjusted distance usually falls between 0 and 1, however it can theoretically surpass 1. Garcia's Monte Carlo simulations with sample sizes of 10, 15, 50, 100, 500, 1,000, and 10,000 indicate that an adjusted distance of 0.1 corresponds to roughly 95% of the consistency lying within an interval of ± 0.1 around the mean consistency, though further empirical studies are required to determine the relevant threshold between 0 and 1 for a particular research setting. Likewise, a 0.2 adjusted distance means that around 95% of the concordance is within a ± 0.2 range around the mean. A certain panel data structure may be present in the dataset if adjusted distances above these thresholds. Significant time effects (such as economic cycle effects) are suggested by high inter-panel consistency adjusted distances.

4.2. Data Sources and Measurement of Variables

4.2.1. Data sources

This study chooses a sample of 30 Chinese provinces' cross-sectional data for the years 2011 to 2022 for empirical research because of the dearth of data in the Tibet region of China and to guarantee data availability and continuity. The

information pertaining to digital finance is taken from the 2022 Digital Inclusive Finance Index published by the Center for Digital Finance Research at Peking University. The China Urban Statistical Yearbook, China Financial Yearbook, China Science and Technology Statistical Yearbook, China Energy Statistical Yearbook, China Provincial Statistical Yearbook, and the yearly national economic and social development statistical bulletin for every province and municipality are the sources of local government spending, the financial development index, and other economic indicators.

4.2.2. Variable measurement

On the measure of the outcome variable. The carbon emission efficiency (Y) is the outcome variable. Using the weighted SBM-DEA model, this work uses MAXdea8 software to determine the carbon emission efficiency of 30 Chinese provinces, including municipalities and autonomous territories. The labor force (as determined by year-end employment in each province), capital stock, and energy consumption (as expressed in 10,000 standard tons of coal) are examples of inputs. Coal, coke, crude oil, gasoline, kerosene, diesel fuel, fuel oil, and natural gas are all included in energy consumption estimations. Zhang Jun et al.'s description of the perpetual inventory method is used to determine the capital stock. The non-desired output is carbon dioxide emissions, while the desired output is real GDP (with 2008 as the base year). The estimating techniques described in the IPCC Guidelines for National Greenhouse Gas Inventories; 2006 Edition (IPCC2006) serve as the foundation for the computation procedure.

Table 1. Descriptive statistics of the variables

variable	sample size	average value	statistics	minimum value	maximum value
Y	360	224.438	106.6744	1.96	431.49
X1	360	239.597	112.5971	6.76	587.65
X2	360	308.125	114.8522	7.58	462.23
X3	360	204.481	94.4802	0	379.51
X4	360	494.669	210.7592	0.25	974.08
X5	360	159.346	73.2567	1.16	325.2
X6	360	0.259	0.1115	0.10500	0.75829
X7	360	1.198	0.8474	0.2016	4.62524
X8	360	3.2854	1.1872	1.27910	8.13103
X9	360	0.0179	0.0301	0.00018	0.19099
X10	360	0.3018	0.1150	0.14904	1

About the measurement of the conditional variable. ①The digital financial index is based on the vast amount of data on digital financial inclusion that the Ant Group provides, as well as the pertinent foundation of the current literature and research. It measures the digital financial inclusion indices at the provincial, city, and county levels. The primary measurement indicators of the digital financial index are the digital financial coverage breadth (X1), digital financial use depth (X2), and the digitization degree of digital financial inclusion (X3). Additionally, the index system is built from the three dimensions of the breadth of digital financial coverage, the depth of digital financial use, and the degree of digitalization of inclusive finance. The breadth of digital financial coverage primarily consists of three indicators: the number of Alipay accounts, the percentage of Alipay card-bound users, and the number of Alipay accounts with card-bound cards. The depth of digital financial use primarily consists of the services of payments, credits, and money funds. The degree of digitalization of inclusive finance also includes

the dimensions of mobile, affordability, and convenience. The insurance dimension is derived from the number of insured users per 10,000 Alipay users, the number of insured pens per capita, and the number of insured pens per capita through dimensionless processing and weighted arithmetic average synthesis model. The payment dimension is derived from the number of payments per capita, the number of payments per capita, and the ratio of the number of high-frequency (active 50 times or more per year) active users to the number of active once or more per year. Through dimensionless processing and a weighted arithmetic mean synthesis model, the credit dimension is derived from the perspective of individuals and small and micro-enterprise operators, respectively, by using the number of Internet consumers (small and micro-enterprise) who have taken out loans, the number of loans per capita (household), and the average loan amount per capita (household) per 10,000 Alipay users. ② Local fiscal expenditures are divided by GDP to determine the extent of government intervention, or X7. ③ The degree of environmental control X8, which is the proportion of GDP that is allocated to environmental governance. The total deposits and loans made by financial institutions at the end of the year divided by GDP represents financial development level X9. ⑤ Regional innovation level X10, calculated by dividing the turnover of the technology market by GDP. Table 1 displays each variable's descriptive statistics.

4.2.3. Data calibration and conversion

Given the number of conditional variables, qualitative comparative analysis tools such as QCA generated based on Boolean algebra and set analysis greatly enhance the matching of the theory and methods of histogram analysis. The set was categorized into three-valued sets, four-valued sets, six-valued sets, and others by pre-set different anchor points. So it is necessary to calibrate the entire sample raw data so that they are classified into the corresponding set intervals as well as given the corresponding affiliation scores to match the Boolean logic of the QCA method. In this thesis, from the practical significance of the sample data, three critical localization points are set in the set of variables using "full affiliation" (0.95), "midpoint" (0.5), and "no affiliation at all" (0.05). Three critical positioning points (anchor points) were set in the set to realize the uniform calibration of the sample data. The calibration information of the sample data is shown in Table 2.

Table 2. Variable calibration results

Variable name		Full affiliation	Intersection point	Totally unaffiliated
outcome variable	Y	0.4765188	0.2782469	0.1752774
conditional variable	X1	375.99149	232.80999	33.599998
	X2	420.12849	246.58000	53.256001
	X3	422.94151	354.08500	44.709001
	X4	337.487	226.285	44.956
	X5	773.2435	528.28	50.647
	X6	276.1195	159.815	42.1315
	X7	0.4504310	0.2313223	0.1290410
	X8	2.9778385	0.9341453	0.3590117
	X9	5.868576	3.0891743	1.8309458
	X10	0.067682	0.0073764	0.0007378
Calibration points of 0.95, 0.5, 0.05				

5. Analysis of Results

5.1. Individual Conditional Necessity Analysis

Qualitative comparative analysis of the calibrated data should first carry out a single condition necessity analysis, so as to determine whether the condition is a necessary condition for the results, the necessity analysis can be obtained after two indicators, namely, consistency and coverage, if the aggregated consistency value of one of the conditions is greater than 0.9 and the aggregated consistency of the coverage of more than 0.5, then this condition is a necessary condition for the results of the condition variable. In this paper, the necessity analysis of all condition variables was performed using R software and the obtained necessity results for each condition variable are shown in Table 3. The table shows some differences between the variables, mainly due to the different correlations between the different parameters.

According to Table 3's findings, there is no required correlation between the conditional variables and carbon emission efficiency since the magnitude of the aggregated consistency results of all the conditional variables is less than 0.9. As a result, none of the conditional variables can be the prerequisites for the outcome variables. This means that the conditional variables must work together to influence the increase in carbon emission efficiency, and the weak influence of a single conditional variable suggests that a number of factors are working together to improve carbon emission efficiency. Therefore, to identify the many pathways of influence on improving carbon emission efficiency, more analysis of various antecedent and causative variables is required. The interplay and effects of several variable factors must be thoroughly taken into account when evaluating the driving influence of digital finance on carbon emission efficiency.

Table 3. Results of necessity analysis for individual conditioning variables

Variable	Y		~Y	
	Aggregate consistency	Aggregate coverage	Aggregate consistency	Aggregate coverage
X1	0.751	0.693	0.576	0.582
~X1	0.547	0.541	0.695	0.754
X2	0.758	0.739	0.535	0.572
~X2	0.562	0.525	0.756	0.773
X3	0.748	0.659	0.627	0.604
~X3	0.551	0.574	0.646	0.737
X4	0.757	0.732	0.524	0.555
~X4	0.54	0.509	0.747	0.771
X5	0.798	0.721	0.596	0.59
~X5	0.547	0.553	0.719	0.796
X6	0.765	0.731	0.539	0.564
~X6	0.544	0.518	0.743	0.776
X7	0.504	0.493	0.799	0.857
~X7	0.854	0.795	0.528	0.538
X8	0.542	0.565	0.69	0.789
~X8	0.797	0.701	0.62	0.597
X9	0.661	0.684	0.591	0.669
~X9	0.68	0.603	0.72	0.7
X10	0.68	0.767	0.481	0.594
~X10	0.64	0.529	0.811	0.735

5.2. Conditional Combination Sufficiency Analysis

For specific studies, the distribution of cases in the evidence table and the investigator's knowledge of the observed cases should also be considered. For small and medium samples, the frequency threshold is 1, while for large samples, the frequency threshold should be greater than 1. The final consistency threshold set for this study was 0.8, the frequency threshold was 2, and the PRI consistency threshold was 0.6. This covers a final sample of 300.

Table 4. Analysis of configuration results

Conditional variable	Group 1	Group 2	Group 3	Group 4	Group 5
Breadth of digital financial coverage	•	•	•	•	⊗
Depth of use of digital finance	•	•	•	•	⊗
Digitization of financial inclusion	•	•	•	•	⊗
Payments	•	•	•	•	⊗
Insurance	•	•	•	•	⊗
Credit	•	•	•	•	⊗
Level of government intervention	⊗	⊗	⊗	⊗	⊗
Level of environmental regulation	⊗		⊗	⊗	⊗
Level of financial development			•	•	•
Level of regional innovation		•	•	•	•
consistency	0.917	0.924	0.922	0.924	0.95
PRI	0.832	0.841	0.818	0.823	0.649
degree of coverage	0.556	0.478	0.389	0.393	0.217
Unique coverage	0.1	0.022	0.001	0.004	0.037
Intergroup consistency adjustment distance	0.0584	0.0506	0.0545	0.0545	0.0467
Intra-group consistency adjustment distance	0.1897	0.1840	0.1725	0.1782	0.1035
Overall consistency			0.917		
Overall PRI			0.832		
Overall coverage			0.621		

Note: • is the presence of marginal conditions; • is the presence of core conditions; ⊗ is the absence of marginal conditions; ⊗ is the absence of core conditions; a blank space means that the condition may or may not be present.

Following the creation of the truth table, three different kinds of solutions are produced by the examination of the

grouping results: the complex solution, the parsimonious solution, and the intermediate solution. Generally, researchers choose the intermediate solution for analysis because it contains the conditions of the parsimonious solution, which is the core variable, while those that do not contain it are the marginal variables. The complex solution does not

incorporate any logical residuals and tends to contain the most configurations, the parsimonious solution incorporates all logical residuals and has the fewest configurations, and the intermediate solution only incorporates the logical residuals that conform to the expectations of the theoretical direction and has a moderate complexity. The findings of the overall grouping analysis, which include three different kinds of a total of five categories, are presented in this paper in Table 4.

5.3. Analysis of Aggregated Results

The summarized results indicate that the five resulting groupings exhibit a consistency level exceeding the minimum acceptable standard of 0.75 for both individual solutions (groupings) and the overall solution, achieving an overall consistency of 0.917 and a coverage of 0.832. It can be inferred that the five groupings presented in the table represent a sufficiently conservative combination to enhance carbon emission efficiency.

In Table 4.6, the following definitions apply: raw coverage denotes the proportion of cases in the HCE outcome explained by the histogram pathway; unique coverage reflects the proportion that can only be accounted for by that pathway; consistency level indicates the proportion of cases with a specific histogram condition that achieve HCE; intergroup consistency-adjusted distance measures the temporal differences for each histogram condition; intragroup consistency-adjusted distance captures the area differences for each grouping condition; overall coverage represents the proportion of all grouping conditions that explain the occurrence of high carbon emission efficiency outcomes; and overall consistency assesses the extent to which all grouping conditions achieve high carbon emission efficiency.

Based on the above findings, this study identifies three types of impact pathways for enhancing carbon emission efficiency.

First, high-quality digital finance is a driving factor. Groupings 1 and 2 demonstrate that digital finance contributes to increasing the depth of its use and the digitization of inclusive finance. This pathway primarily involves the development of high-quality digital finance with minimal government intervention and reduced environmental regulations to enhance carbon emission efficiency. In regions with established digital financial systems, online digital financial platforms facilitate more efficient and rapid trading of carbon financial products, allowing market funds to flow more swiftly and thereby stimulating the carbon market to promote carbon emission reductions. Conversely, excessive government intervention may diminish the efficiency of carbon emissions.

Second, digital innovation is a collaboratively driven factor. Configurations 3 and 4 indicate that the increase in regional innovation levels plays a central role. Furthermore, configuration 3 illustrates that the combination of a high level of regional innovation and advanced digital financial development, along with appropriate government intervention, significantly enhances carbon emission efficiency. This pathway emphasizes robust scientific and technological innovation development within an improved digital financial landscape. It leverages enterprise green technologies to enhance carbon emission efficiency, while excessive government intervention may lead to resource misallocation, thereby reducing carbon emission efficiency.

Third, optimization is needed for the synergy between digital finance and innovation. Panel 5 indicates that regional

innovation levels contribute to the enhancement of financial development. This pertains to provinces in the early stages of digital finance development, where overall advancements need optimization. High levels of environmental regulation and regional innovation are essential for improving carbon emission efficiency. The breadth of digital finance coverage, depth of use, and digitization of financial inclusion in this context need to be strengthened. With the combined support of relaxed environmental regulations, minimal government intervention, and advances in scientific and technological innovation, carbon emission efficiency can also be enhanced.

5.4. Policy Recommendations

Based on the study's findings, we propose several specific policy recommendations. First, the advancement of the digital economy should be expedited to promote the deep integration of digital technology across various industries and facilitate decarbonization. Empirical studies have demonstrated that the development of a digital economy can enhance carbon efficiency. By increasing the adoption of digital technologies across various sectors—such as manufacturing, daily life, transportation, and energy the efficiency and competitiveness of these sectors can be enhanced. Subsequently, digital technology can facilitate the acceleration of enterprise digital transformations. By optimizing and integrating key processes and business units—such as production, research and development, and sales—enterprises can achieve higher quality and efficiency, ultimately increasing resource efficiency and reducing energy consumption.

Second, the research and technological development of key low-carbon technologies should be reinforced. Empirical tests have confirmed the synergistic effects of STI and digital financing. The foremost challenge in fully promoting STI is the establishment of a supportive policy environment. This involves crafting a comprehensive set of policies and regulations closely aligned with STI, continuously improving environmental laws and regulations, and ensuring a fair and multifaceted playing field and policy framework. Additionally, it is essential to promote the extensive application of STI advancements across various fields. In sectors such as industry, agriculture, construction, and transportation, the application of scientific and technological innovations should be encouraged to effectively foster energy conservation and emission reduction.

Third, a harmonious balance between economic growth and environmental protection must be achieved, while upholding the concept of sustainable development. Environmental regulation and digital finance can synergistically enhance carbon efficiency. In this context, measures to promote sustainable development and address the relationship between environmental protection and economic growth should be highlighted. First, enhancing interregional cooperation is essential. This cooperation can mitigate harmful competition, allowing for collaborative efforts in advancing the digital economy and ensuring the rational allocation and efficient utilization of resources. Second, it is vital to accelerate the application of renewable energy within the digital infrastructure sector. This approach will not only decrease carbon emissions associated with digital infrastructure but also facilitate the low-carbon transformation of digital infrastructure development.

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