科学学研究
STUDIES IN SCIENCE OF SCIENCE
中国科学学与科技政策研究会
中国科学院科技战略咨询研究院
清华大学科学技术与社会研究中心
ISSN 1003-2053 CN 11-1805/G3

Assessing the Contribution of Green Finance and Digital Economic Development to Regional Carbon Emission Mitigation

评估绿色金融与数字经济发展对区域碳排放减缓的贡献

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Abstract. This study examines the relationship between green finance, the digital economy, and efforts to reduce carbon emissions. The analysis employs a comprehensive dataset covering the period from 2010 to 2022, collected from thirty-one provinces, autonomous regions, and municipalities across China. The findings reveal several important insights. First, green finance plays a significant role in promoting regional carbon emission reduction. Similarly, the development of the digital economy also contributes to lowering regional carbon emissions. Furthermore, green technology innovation serves as a key moderating factor in the relationship between green finance and carbon emission mitigation. The results also indicate the presence of a threshold effect in the influence of green finance on regional carbon emission reduction, with varying impacts depending on regional population size. In addition, the contribution of green finance to carbon emission reduction differs across regions, with the strongest impact observed in western China, followed by the central region, while its effect in the eastern region is relatively weaker. Likewise, the digital economy demonstrates regional variations in its influence on carbon emission reduction, showing a stronger contribution in eastern regions, whereas its effect appears less pronounced in the central and western regions.

Keywords: Green finance; Digital economy; Carbon emission reduction

摘要： 本研究探讨绿色金融、数字经济与碳排放减缓之间的关系。研究采用2010年至2022年中国31个省、自治区和直辖市的数据进行分析。研究结果表明：第一，绿色金融在促进区域碳排放减少方面发挥了显著作用；同时，数字经济的发展也有助于降低区域碳排放。其次，绿色技术创新在绿色金融与碳减排之间发挥了重要的调节作用。研究结果还表明，绿色金融对区域碳减排的影响存在门槛效应，其作用会随着区域人口规模的不同而呈现差异。此外，绿色金融在不同地区对碳减排的贡献存在明显差异，其中西部地区的影响最为显著，其次为中部地区，而在东部地区的影响相对较弱。同样，数字经济在促进碳减排方面也表现出区域差异，在东部地区的作用更为明显，而在中部和西部地区的影响相对较弱。

关键词： 绿色金融，数字经济，碳排放减少

Received:	12 December 2025	Revised:	2 January 2025	Accepted:	27 January 2026	Published:	14 February 2026

Citation: Huang, Y., Nui, L., & Zhou, X. (2026). Assessing the contribution of green finance and digital economic development to regional carbon emission mitigation: 评估绿色金融与数字经济发展对区域碳排放减缓的贡献. *Studies in Science of Science*, 44(2), 159–174.

1. Introduction

Globally, climate change has emerged as a critical challenge, and the issue of carbon emissions has gained increasing international attention. In 2023, China's greenhouse gas emissions reached approximately 12.6 billion tons of CO_2 equivalent, representing a 4.13% increase from 12.1 billion tons recorded in 2022, or an additional 565 million tons of emissions. As one of the largest carbon dioxide emitters worldwide, China's policies and progress in reducing carbon emissions carry substantial implications for global climate mitigation efforts (Mohsin et al., 2021). In recent years, green finance and the digital economy have increasingly been recognized as important drivers of sustainable economic development, attracting considerable attention from both scholars and policymakers. Green finance refers to financial activities designed to support environmental protection, climate change mitigation, and efficient resource utilization. Meanwhile, the digital economy leverages digital technologies to enhance productivity and improve the efficiency of economic activities (Paramati et al., 2021).

Green finance, the digital economy, and carbon emission reduction are closely interconnected (Yu et al., 2022). Green finance mobilizes financial resources to support initiatives aimed at environmental preservation and sustainable growth. Through financial instruments and investments, it provides funding for the development and application of low-carbon technologies, thereby directly contributing to emission reduction efforts (Dong et al., 2022). At the same time, the digital economy improves resource efficiency through the application of digital technologies, which can lower carbon emissions per unit of GDP. Moreover, the rapid expansion of the digital economy broadens the scope of green finance applications, generating a complementary relationship between the two. Together, these mechanisms facilitate the transition toward a greener and low-carbon economic structure. Although previous studies have examined the influence of green finance and the digital economy on economic development, their specific roles and the mechanisms through which they contribute to carbon emission reduction remain areas that require further investigation.

Green finance and the digital economy are increasingly recognized as key factors supporting global carbon emission reduction (Wang et al., 2022). Green finance promotes environmental sustainability by providing innovative financial mechanisms that support the development and implementation of low-carbon technologies (Li & Wang, 2022). Simultaneously, the digital economy offers new pathways for reducing carbon emissions by enhancing resource efficiency and lowering emissions intensity per unit of GDP. Nevertheless, existing research still presents several limitations. Current quantitative frameworks assessing the contribution of the digital economy to carbon reduction remain relatively underdeveloped, restricting a comprehensive evaluation of its overall impact. Furthermore, limited attention has been given to exploring the mechanisms and policy approaches through which green finance and the digital economy can effectively interact to promote carbon emission reduction.

This study seeks to address this research gap by empirically examining the effects of green finance and the digital economy on provincial carbon emission reduction in China, including provinces, municipalities, and autonomous regions. The primary objective is to determine whether these two factors significantly contribute to regional carbon emission reduction and whether green technological innovation acts as a key mediating mechanism within this relationship. Using panel data covering the period from 2010 to 2022 across 31 provincial regions in China, the findings demonstrate that both green finance and the digital economy play significant roles in reducing carbon emissions. In addition, the study identifies the moderating influence of green technological innovation in strengthening the relationship between green finance and carbon emission mitigation, emphasizing the critical role of technological advancement in achieving decarbonization targets. The effectiveness of green finance in reducing carbon emissions also varies across regions, which may be influenced by differences in economic development levels, industrial structures, and policy environments.

The significance of this study lies in its contribution to understanding how green finance and the digital economy can jointly promote carbon emission reduction. The results provide valuable insights for policymakers in designing more effective carbon mitigation policies while also offering guidance for financial institutions and businesses on leveraging green finance and digital technologies to support sustainable development. Furthermore, the study highlights the crucial role of green technological innovation in achieving carbon emission reduction, emphasizing that technological advancement is essential for reaching carbon neutrality goals. Overall, this study contributes by proposing a comprehensive analytical framework that links green finance, the digital economy, and carbon emission reduction while examining the complex interactions among these factors. The findings are particularly important for understanding the key drivers of China's progress toward carbon reduction targets and may also offer relevant insights for other developing economies seeking sustainable pathways for environmental and economic development.

2. Materials and Methods

Green finance, which refers to financial mechanisms designed to support environmentally sustainable activities, influences regional carbon emissions through several pathways. By allocating financial resources to sectors such as environmental protection, energy conservation, and renewable energy development (Le et al., 2020), green finance promotes the expansion of industries characterized by high energy efficiency and relatively low carbon emissions. Consequently, the integration of green financial instruments contributes to reducing carbon output. In addition, green finance redirects socio-economic resources toward environmentally sustainable and low-carbon activities by adjusting the allocation of funds within financial institutions and encouraging investment in environmentally friendly industries. This shift in financial flows can gradually facilitate the transformation of high-emission industries, thereby contributing to carbon emission reduction (Lv & Bai, 2021). Moreover, green finance supports the development and diffusion of green technologies, including renewable energy solutions as well as technologies focused on energy conservation and emission reduction (Kadefors et al., 2021). The adoption of such technologies improves energy efficiency and significantly lowers carbon footprints. Furthermore, the promotion of green finance enhances environmental awareness throughout society, encouraging both firms and individuals to engage in environmentally responsible behavior and adopt low-carbon lifestyles, which ultimately contributes to reducing carbon emissions in everyday activities (Guo & Zhang, 2023). Based on this reasoning, the study proposes the following hypothesis.

H1. *Green finance can facilitate regional carbon emissions reduction.*

The digital economy also affects regional carbon emissions through multiple mechanisms. It contributes to emission reduction by promoting the digitalization, environmental sustainability, and smart transformation of infrastructure systems (Yu et al., 2020). For instance, intelligent energy management technologies can significantly enhance energy efficiency, thereby reducing both energy waste and carbon emissions (Renzhi & Baek, 2020). Furthermore, the digital economy promotes industrial digitization and the expansion of digital industries, which in turn accelerates industrial upgrading. This structural transformation reduces the share of traditional high-carbon industries, contributing to a decline in overall carbon emissions (Chen et al., 2022). Digital technologies also enable a more efficient allocation of economic resources through advanced data analytics and improved management systems, reducing inefficiencies and lowering overall societal carbon emissions (Bingler et al., 2022). Additionally, digital technologies such as big data and cloud computing stimulate technological innovation and facilitate the development of new digital solutions for carbon reduction, strengthening the technological foundation for emission mitigation (Song et al., 2021). The digital economy also affects supportive mechanisms, including financial lending, industrial clustering, and foreign investment, which encourage the development of environmentally sustainable industries and green economic activities, ultimately contributing to lower carbon emissions (Jin et al., 2020). Based on this reasoning, the study proposes the following hypothesis.

H2. *The regional carbon emissions can be mitigated through the advancement of the digital economy.*

Green technological innovation, including renewable energy technologies as well as solutions aimed at energy efficiency and pollution control, plays a crucial role in improving resource utilization and energy efficiency, which consequently reduces carbon emissions per unit of output (Zhang, 2021). These innovations also expand the range of profitable low-carbon investment opportunities, thereby strengthening the effectiveness of green finance in promoting carbon reduction (Tan et al., 2020). By directing investments toward green technological innovation projects, green finance enables a more efficient allocation of resources to sectors capable of achieving substantial emission reductions (Baker et al., 2021). Such targeted financial support accelerates the research, development, and deployment of environmentally friendly technologies, thereby amplifying the emission reduction effect of green finance (Wen et al., 2021). Moreover, green technological innovation reduces the operational costs of green projects while enhancing their profitability and competitiveness in the market, making green finance investments more attractive (Ren et al., 2021). This positive feedback mechanism encourages greater participation of social capital in green industries, promoting the expansion of the green finance market and further strengthening carbon emission reduction efforts (Murinde et al., 2022). Based on this reasoning, the study proposes the following hypothesis.

H3. *Green technological innovation exerts a notable moderating effect on the correlation between green finance and carbon emission reduction.*

Population size represents an important factor influencing carbon emissions and is closely associated with the effectiveness of green financial policies. Regions with high population density typically experience more intensive economic activities and daily consumption patterns, which often result in higher carbon emission levels (Gu et al., 2021). In such contexts, green finance becomes particularly important, as it can guide capital flows toward energy-saving and emission-reduction projects through policy direction, resource allocation, and technological support. These mechanisms help stimulate technological transformation and industrial upgrading in industries with high energy consumption and pollution levels, thereby reducing carbon emissions (Sun et al., 2020). However, the carbon reduction effect of green finance does not increase linearly and may be constrained by various factors, including economic development levels, industrial structures, and technological capabilities, resulting in a threshold effect (Zhang et al., 2020). Specifically, once population size surpasses a certain threshold, the emission reduction impact of green finance may reach an inflection point. Before this threshold, increased investment in green finance gradually improves emission reduction outcomes; beyond this point, however, economic, technological, and resource limitations may reduce the marginal benefits of green finance, potentially leading to diminishing emission reduction effects (Shang et al., 2023). Moreover, demographic characteristics and education levels across regions also affect the effectiveness of green finance policies. Regions with higher levels of human capital and innovation capacity are more likely to generate significant green technological innovations through green finance, thereby achieving greater emission reductions (Chen et al., 2023). In contrast, regions with lower innovation capacity may rely more heavily on policy interventions and resource allocation to achieve similar outcomes. Based on this reasoning, the study proposes the following hypothesis.

H4. *The influence of green finance on regional carbon emission reductions demonstrates a threshold effect, with varying characteristics contingent upon shifts in regional population size.*

In economically advanced regions, such as eastern China, green finance tends to develop more rapidly. These regions possess stronger economic capacity and greater financial resources, enabling them to invest more effectively in green finance initiatives that support carbon emission reduction (Adams et al., 2020). Conversely, in less economically developed regions, particularly western China, the development of green finance may progress more slowly, resulting in a weaker influence on carbon emission mitigation. This disparity may be associated with limitations in funding availability, technological capacity, and market accessibility (Zhou & Wang, 2022). Industrial structure also plays a direct role in determining carbon emission levels. Regions dominated by heavy industries, including certain resource-based cities, typically exhibit higher carbon emission intensity (Lee & Wang, 2022). In such areas, although green finance can still support emission reduction efforts, it may encounter greater challenges. Conversely, in regions where high-technology industries and service sectors are more prominent, the relatively lower emission intensity of these industries enables green finance to contribute more effectively to emission reduction (Xiang et al., 2022). In addition, local government policy support significantly influences the effectiveness of green finance in reducing carbon emissions. Regions with strong policy incentives, including tax reductions and financial subsidies, are more capable of encouraging green finance development and supporting environmentally friendly industries, thereby improving emission reduction outcomes. In contrast, areas with limited policy support may experience weaker emission reduction effects from green finance (Wang & Lee, 2022). Based on this reasoning, the study proposes the following hypothesis.

H5. *The effect of green finance on decreasing carbon emissions exhibits regional disparities.*

The influence of the digital economy on carbon emission reduction may also differ across regions due to variations in economic development levels, industrial composition, technological innovation capacity, and resource endowments (Li & Wang, 2022). Regions with higher levels of economic development, particularly eastern coastal areas, generally possess more advanced digital infrastructure and greater levels of digital technology adoption. This allows them to utilize digital technologies more effectively to optimize resource allocation, improve production efficiency, and accelerate the transition toward green and low-carbon industrial structures (Zhang et al., 2023). At the same time, industrial structure differences also contribute to the heterogeneous effects of the digital economy on carbon reduction. In regions dominated by heavy industries, the digital economy may generate some energy-saving benefits; however, the overall carbon reduction impact may remain limited due to the high share of energy-intensive industries. In contrast, regions with larger service and high-technology sectors tend to experience more significant emission reductions through digitalization because these sectors rely less heavily on energy resources and are more adaptable to digital transformation. Technological innovation capacity further shapes regional differences in the carbon reduction effects of the digital economy. Regions with strong innovation capabilities can more rapidly adopt emerging digital technologies and integrate them with green technological development, thereby achieving more effective carbon reduction. Conversely, regions with weaker innovation capacity may face challenges such as technological barriers and shortages of skilled labor, which restrict the digital economy's potential in reducing emissions. Additionally, differences in natural resource endowments also influence the effectiveness of the digital economy in supporting carbon reduction. Regions with abundant renewable energy resources, such as solar and wind energy, can more easily optimize their energy structures when developing the digital economy and substitute fossil fuels with cleaner energy sources. In contrast, regions with limited natural resources may face greater difficulties in achieving emission reduction goals. Based on this reasoning, the study proposes the following hypothesis.

H6. *The impact of the digital economy on carbon emission reduction varies across different regions.*

This study collected data from several authoritative sources, including the official websites of the National Bureau of Statistics, the Ministry of Science and Technology, and the People's Bank of China, along with several annual statistical reports. To ensure the reliability and credibility of the dataset, a rigorous verification process was conducted. Data obtained from multiple sources were cross-checked and evaluated for logical consistency to minimize possible discrepancies. Through this careful validation procedure, the dataset achieved a high level of accuracy and reliability, thereby providing a strong empirical foundation for the subsequent analysis. The dependent variable in this study is carbon emission reduction (carbon), which is measured using the logarithmic value of total carbon emissions for each province during the period 2010–2022. The calculation adopts the latest carbon accounting framework that includes Scope 1, Scope 2, and Scope 3 emissions. Scope 1 represents direct emissions occurring within the administrative boundary of each province, including emissions generated from transportation, construction activities, industrial production processes, land-use changes in agriculture and forestry, and waste management. Scope 2 represents indirect emissions related to energy consumption outside the provincial boundary, mainly originating from electricity, heating, and cooling purchased for local use. Scope 3 includes other indirect emissions generated from provincial activities but occurring beyond its geographical boundary, excluding Scope 2 emissions. These emissions include greenhouse gases generated from the production, transportation, use, and disposal of goods imported from outside the province. Therefore, total carbon emissions are calculated as the sum of Scope 1, Scope 2, and Scope 3 emissions.

The main independent variables used in this study are green finance (gfinance) and digital economy (idf). Green finance is measured using an entropy-based comprehensive evaluation system that consists of seven indicators, including green credit, green investment, green insurance, environmental protection bonds, green guarantees, green financial funds, and ecological equity participation. Meanwhile, the level of digital economy development is measured using the Digital Financial Inclusion Development Index, which reflects the degree of digital financial services and technological adoption in each region. In addition, green technology innovation level (gi) is introduced as a moderating variable. This variable is measured using the logarithmic value of the number of green patent applications, which serves as a proxy indicator of green technological innovation. Compared with patent authorization data, patent application data are considered more timely and stable in capturing innovation activities. The data were obtained from the China Wen Data Service Platform.

Several control variables are included to account for regional socio-economic differences. These include economic development level (eco) measured by real GDP per capita; population size (size) measured by the logarithm of the permanent resident population; urbanization level (ctt) measured by the proportion of urban residents in the total population; population aging (pa) measured by the proportion of individuals aged 65 and above; human capital level (hum) measured by the average years of schooling per capita; public service expenditure (public) measured by the logarithm of government public service expenditure; industrial structure (structure) measured by the ratio of tertiary industry value added to GDP; and opening level (open) measured by the ratio of total imports and exports to regional GDP. The definitions of all variables are summarized in Table 1.

Table 1. Definition of variables.

Variable type	Variable name	Variable symbol	Variable definition
Dependent variable	Carbon emission reduction	carbon	Ln (total carbon emissions)
Independent variables	Green finance	gfinance	A comprehensive index evaluation system constructed using the entropy method through seven indicators
	Digital economy	idf	The Digital Financial Inclusion Development Index
Moderator variable	Green technology innovation level	gi	Ln (number of green patent applications)
Control variables	Economic development level	eco	Per capita real GDP of each province
	Population size	size	Ln (permanent resident population / total population)
	Urbanization level	ctt	Urban permanent resident population / total population
	Population aging	pa	Population aged 65 and over / total population
	Human capital level	hum	Years of education per capita in the region
	Public service expenditure	public	Ln (general public service expenditure)
	Industrial structure	structure	Added value of tertiary industry / GDP
	Opening level	open	Total import and export volume / regional GDP

To test the proposed hypotheses, panel regression models are constructed. The first model examines the effect of green finance on carbon emission reduction while controlling for other variables:

$$carbon_{i,t} = \alpha^0 + \alpha^1 gfinance_{i,t} + \Sigma_{k=1}^{n} \alpha_k control_{i,t} + \varepsilon_{i,t} \quad (1)$$

Model (2) examines the influence of the digital economy on carbon emissions:

$$carbon_{i,t} = \beta^0 + \beta^1 idf_{i,t} + \Sigma_{k=1}^{n} \beta_k control_{i,t} + \varepsilon_{i,t} \quad (2)$$

Model (3) incorporates the interaction between green finance and green technological innovation to test the moderating role of green technological innovation:

$$carbon_{i,t} = \delta^0 + \delta^1 gfinance_{i,t} + \delta^2 gi_{i,t} + \delta^3 (gfinance_{i,t} \times gi_{i,t}) + \Sigma_{k=1}^{n} \delta_k control_{i,t} + \varepsilon_{i,t} \quad (3)$$

These models allow the study to empirically evaluate the relationships among green finance, the digital economy, green technological innovation, and regional carbon emission reduction.

3. Result and Discussion

The descriptive statistics presented in Table 2 provide an overview of the key variables used in this study. The values for carbon emissions (carbon) range from 8.8914 to 11.0134, indicating considerable differences in the level of carbon emission control among regions. The green finance index (gfinance) varies between 0.0904 and 0.5777, suggesting notable disparities in the development of green finance across different regions. Similarly, the digital economy index (idf) ranges from 2.936 to 6.0991, highlighting substantial regional variation in the advancement of digital economic activities. The average level of economic development (eco) is 10.8069, which reflects a relatively stable and generally high economic condition across the observed regions. The average logarithmic value of population size (size) is 8.1286, with a standard deviation of 0.8413, indicating considerable regional differences in population distribution. The urbanization level (ctt) has a mean value of 0.5803 and a standard deviation of 0.1321, demonstrating varying stages of urbanization among regions. Meanwhile, population aging (pa) records an average value of 0.1084 with a standard deviation of 0.0293, suggesting that the aging structure of the population is relatively similar across regions. The human capital level (hum) shows an average of 9.1162 and a standard deviation of 1.1335, indicating significant differences in educational attainment between regions. In addition, public service expenditure (public) and industrial structure (structure) display varying patterns across regions, while the opening level (open) also shows considerable variation, reflecting differences in the degree of regional economic openness.

Table 2. Descriptive statistical analysis.

VarName	Obs	Mean	SD	Min	Median	Max
carbon	403	10.2435	0.7300	8.8914	10.4704	11.0134
gfinance	403	0.3133	0.1265	0.0904	0.3477	0.5777
idf	403	5.3310	0.8449	2.9360	5.4703	6.0991
gi	403	7.6903	1.0344	2.0794	7.8932	10.7485
eco	403	10.8069	0.4835	9.7406	10.7909	12.0088
size	403	8.1286	0.8413	5.7838	8.2563	9.4212
ctt	403	0.5803	0.1321	0.2375	0.5698	0.8930
pa	403	0.1084	0.0293	0.0547	0.1038	0.1812
hum	403	9.1162	1.1335	5.0712	9.1390	12.5430
public	403	5.9302	0.6707	4.1220	5.9817	7.3501
structure	403	0.4938	0.0899	0.3389	0.4885	0.8209
open	403	0.2911	0.3093	0.0130	0.1548	1.4344

The regression results of Model 1 and Model 2 are reported in Table 3. As shown in column (1), the coefficient of green finance is −3.9222 and is statistically significant, indicating that green finance has a strong effect in reducing regional carbon emissions. This finding supports Hypothesis 1. Furthermore, the results presented in column (2) show that the coefficient of the digital economy is −0.5166, which is statistically significant at the 1% level. This result suggests that the development of the digital economy also contributes positively to reducing regional carbon emissions, thereby providing empirical support for Hypothesis 2.

Table 3. Results of the main regression test.

Variables	(1) carbon	(2) carbon
gfinance	-3.9222***	
	(-44.2401)	
idf		-0.5166***
		(-2.8589)
eco	-0.1491***	-0.4205***
	(-3.3029)	(-3.6979)
size	0.0448	0.1538**
	(1.6420)	(2.2893)
ctt	0.0826	-0.8999
	(0.3102)	(-1.3779)
pa	-0.0939	0.9222***
	(-1.3559)	(5.8280)
hum	0.0604***	0.1024***
	(3.4551)	(3.5820)
public	0.0851***	0.0733
	(2.0747)	(0.9084)
structure	0.2134	0.3587
	(1.1427)	(0.7830)
open	0.0503	0.7947***
	(0.7029)	(4.2111)
_cons	9.2360***	8.0731***
	(22.0458)	(6.0973)
N	403	403
R^2	0.9278	0.5061
F	233.0469	23.0658

Table 4. Moderating effect results

Variables	(1) carbon	(2) carbon
gfinance	-3.9051***	-6.1794***
	(-46.0163)	(-20.1565)
gi	-0.1118***	-0.1787***
	(-6.0240)	(-9.2303)
gfinance × gi		-0.3067***
		(-7.6781)
eco	-0.2448***	-0.1919***
	(-5.3190)	(-4.4190)
size	-0.1174***	-0.0974***
	(-3.1325)	(-2.7819)
ctt	-0.2850	0.1426
	(-1.0882)	(0.5697)
pa	-1.1199***	-1.3101***
	(-2.2639)	(-2.8391)

hum	0.0767***	0.0173
	(4.2958)	(0.9452)
public	0.1046***	0.1145***
	(3.2680)	(3.8374)
structure	0.1328	0.4170**
	(0.7413)	(2.4388)
open	-0.0026	-0.0189
	(-0.0351)	(-0.2684)
_cons	10.8023***	9.7319***
	(22.6123)	(20.8695)
N	403	403
R^2	0.9341	0.9429
F	244.7073	272.3279

The results presented in Table 4 reveal the moderating role of green technological innovation in the relationship between green finance and carbon emission reduction. As shown in column (2), the coefficients for green finance (gfinance) and green technological innovation (gi) are both negative and statistically significant, indicating that these two factors contribute positively to reducing regional carbon emissions. In addition, the coefficient of the interaction term (gfinance × gi) is 0.3067 and is significant at the 1% level. This result suggests that the level of green technological innovation strengthens the impact of green finance on carbon emission reduction. In other words, higher levels of green technological innovation enhance the effectiveness of green finance in promoting emission mitigation. Therefore, these findings confirm that green technological innovation plays an important moderating role in the relationship between green finance and carbon emission reduction, providing empirical support for Hypothesis 3.

Table 5. Threshold effect test (1)

Model	Threshold	Lower	Upper
Th-1	0.4505	0.3699	0.5191
Th-2-1	0.4505	0.3801	0.5191
Th-2-2	5.8972	5.8289	6.3421
Th-3	0.3801	0.3578	0.5191

Table 6. Threshold effect test (2)

Threshold	RSS	MSE	Fstat	Prob	Crit10	Crit5	Crit1
Single	3.7508	0.0096	42.19	0.0074	10.5819	13.6100	20.5113
Double	3.6248	0.0093	13.55	0.1167	14.0245	16.7741	25.3970
Triple	3.5627	0.0091	6.80	0.4500	15.9970	19.4518	23.1940

To further test Hypothesis 4, this study adopts population size as the threshold variable and initially conducts a triple-threshold regression analysis. The results of the threshold tests, reported in Tables 5 and 6, show that the first-order threshold effect is statistically significant at the 1% level (P = 0.0000), with a threshold value of 6.4505. Based on these results, the analysis proceeds with a single-threshold regression model, and the results are presented in Table 7. The findings indicate that when the regional population size is below 6.4505, the coefficient of green finance (gfinance) is −1.9039 and is statistically significant at the 1% level, suggesting that green finance effectively contributes to reducing regional carbon emissions. However, when the population size exceeds the threshold value of 6.4505, the emission reduction effect of green finance becomes significantly weaker. These results support Hypothesis 4, which proposes that the influence of green finance on carbon emission reduction is subject to a threshold effect associated with population size. As population levels increase, economic activities and living demands expand, leading to higher energy consumption. Although green finance can guide investment toward environmentally friendly projects and encourage the development of low-carbon technologies, the rapid growth of energy demand in densely populated areas may offset part of the emission reduction benefits generated by green finance. Furthermore, population growth can also increase emissions in sectors such as transportation and construction, where emission reduction remains more difficult, thereby weakening the overall effectiveness of green finance.

Table 7. Single threshold regression results

Variables	carbon
0_cat#c.gfinance	-1.9039***
	(-12.0671)
1_cat#c.gfinance	-0.3704**
	(-2.4928)
eco	-0.1076***
	(-3.7007)
ctt	0.5700
	(1.6028)
pa	0.4776
	(1.0301)
hum	0.0434*
	(1.8181)
public	0.1051***
	(3.3127)
structure	0.3179
	(1.3468)
open	-0.0611
	(-0.9520)
_cons	8.3840***
	(13.1043)
N	403
R^2	0.5149
F	309.3509

To explore potential regional differences in the impact of green finance, this study applies a sample partitioning approach and performs grouped regression analysis. The results presented in Table 8 indicate that green finance promotes carbon emission reduction in the eastern, central, and western regions. However, the magnitude of this effect varies across regions. The strongest emission reduction effect is observed in the western region, followed by the central region, while the effect is relatively weaker in the eastern region. These findings demonstrate clear regional heterogeneity in the effectiveness of green finance in reducing carbon emissions, thereby supporting Hypothesis 5. The stronger effect in the western region can be attributed to the abundance of renewable energy resources, which allows green investments to more effectively support structural transformation. In the central region, the transition of traditional industries relies heavily on financial support from green finance. In contrast, the eastern region exhibits a relatively smaller effect because of its already advanced economic structure, limited remaining potential for emission reduction, and greater reliance on efficient energy systems, which leads to diminishing marginal returns from green finance investments.

Table 8. Results of heterogeneity test (1)

Variables	Eastern regions (carbon)	Central regions (carbon)	Western regions (carbon)
gfinance	-2.0826***	-4.0737***	-4.0773***
	(-15.8481)	(-11.4508)	(-24.0641)
eco	-0.0987**	-0.1249	-0.1400
	(-3.0847)	(-0.8582)	(-0.7630)
size	0.0210	0.0374	-0.1455*
	(0.8987)	(0.3616)	(-1.8841)
ctt	-0.0965	-1.1442**	-0.2401
	(-0.3335)	(-2.1713)	(-0.2854)
pa	-1.5695***	2.3953	5.0317***
	(-3.9287)	(1.3099)	(3.3038)
hum	0.0134	0.2507***	0.0331
	(0.4589)	(4.9414)	(0.6319)
public	-0.0210	-0.0880	0.1833*
	(-0.7076)	(-0.8377)	(1.3093)
structure	-0.5939**	-0.4092	-1.1070*
	(-2.3531)	(-1.1598)	(-1.0768)
open	0.3071***	0.1888	-0.3150
	(3.7707)	(1.4705)	(-1.0553)
_cons	10.0625***	8.8103***	10.4050***
	(31.1854)	(5.7806)	(5.5184)
N	109	104	130
R^2	0.9349	0.9068	0.9506
F	100.4513	95.0498	98.8057

To further examine whether the impact of the digital economy on carbon emission reduction differs across regions, this study conducts a subsample regression analysis. The results shown in Table 9 indicate that for the eastern region, the regression coefficient of the digital economy variable (idf) is −0.1607 and is statistically significant at the 1% level. This finding suggests that the development of the digital economy plays a significant role in reducing carbon emissions in eastern China. However, for the central and western regions, the coefficients of the digital economy variable (idf) are not statistically significant, indicating that its impact on carbon emission reduction in these regions is relatively limited. Overall, these results reveal clear regional heterogeneity in the effect of the digital economy on carbon emission mitigation, thereby confirming Hypothesis 6.

Table 9. Results of heterogeneity test (2)

Variables	Eastern regions (carbon)	Central regions (carbon)	Western regions (carbon)
idf	-0.1607***	-0.0019	0.0077 (0.0987)
	(-5.0728)	(-0.0309)	
eco	0.0407	0.0306	-1.4194***
	(0.7694)	(0.1228)	(-3.9108)
size	0.1061***	0.8773***	-0.7094***
	(4.1709)	(6.2925)	(-4.1818)
ctt	2.2465***	-2.2068***	1.1970
	(5.0337)	(-2.7404)	(0.5971)
pa	-1.8583***	0.1016***	23.1144***
	(-2.7907)	(3.7613)	(7.8075)
hum	0.0007	0.2890***	0.2033
	(1.4545)	(4.0150)	(1.7547)
inst	-0.2335***	-0.1642	0.8519***
	(-5.5197)	(-0.9866)	(3.6959)
structure	-0.7069**	1.0203*	-2.3289**
	(-2.4032)	(1.8333)	(-2.0292)
open	-0.0400	0.8744***	-0.8575
	(-0.4030)	(5.2001)	(-1.0500)
_cons	7.8278***	0.8903	22.0953***
	(13.7933)	(0.3804)	(6.7346)
N	109	104	130
R^2	0.7596	0.8501	0.6503
F	55.8279	59.2112	24.7972

Table 10. Endogeneity test results

Variables	(1) Phase I gfinance	(2) Phase II L.gfinance
L.gfinance	1.0226***	
	(181.5509)	
gfinance		-3.8945***
		(-44.0259)
Control variable	Yes	Yes
Year	Yes	Yes
Non-identifiability test	307.960***	
Weak instrumental variable	32960.00	

To address potential endogeneity concerns, this study employs the lagged one-period green finance variable (L.gfinance) as an instrumental variable and applies the two-stage least squares (IV-2SLS) estimation method. The results of the endogeneity test are reported in Table 10. In the first-stage regression, the coefficient of the lagged green finance variable (L.gfinance) is 1.0226 and statistically significant at the 1% level, indicating that it is a valid and relevant instrumental variable for green finance. In the second-stage regression, the coefficient of green finance (gfinance) is −3.8945 and remains significant at the 1% level. This result confirms that, even after controlling for potential endogeneity issues, green finance continues to exert a significant negative effect on carbon emissions, thereby supporting the robustness of the main empirical findings.

4. Conclusions and Implications

Regression results indicate that both green finance and the digital economy play significant roles in reducing regional carbon emissions. Green technological innovation acts as an important mediating mechanism linking green finance to emission reduction. The growth of green patent applications reflects increasing innovation activity, which strengthens the effectiveness of green finance in promoting decarbonization. Furthermore, the heterogeneity analysis reveals substantial regional differences in the impact of green finance on emission reduction, largely driven by disparities in economic development, industrial structures, and policy environments across eastern, central, and western regions.

These findings provide empirical evidence on the interaction between green finance, the digital economy, and carbon emission reduction, highlighting the critical roles of financial support, digital development, and technological innovation in achieving low-carbon transformation. The results also emphasize the importance of region-specific policy approaches. First, governments should strengthen green finance policies by encouraging financial institutions to increase investments in environmentally friendly projects, particularly in central and western regions where the potential for emission reduction is greater. Second, the development of the digital economy should be accelerated by improving digital infrastructure and promoting the integration of digital technologies in economic activities. Third, governments should further support green technological innovation through increased research funding, incentives for corporate innovation, and wider technology adoption. Finally, considering the threshold effect of green finance, policymakers should design differentiated green finance policies that account for regional population size and economic development conditions to maximize the effectiveness of carbon emission reduction efforts.

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