The Impact Mechanism of Green Finance on Carbon Emission Reduction: An Empirical Analysis Using China's Provincial Panel Data

Susu Li [1], Jingyi Liang [1], Ping Jiao [2], Junjun Fei [3]

[1] International Business School, Guangdong University of Finance and Economics,510000, China

[2] Institute of Commerce and Circulation, Guangdong University of Finance and Economics,510000, China

[3] Sichuan Academy of Social Sciences,610500, China

Corresponding Email: susanyun@126.com

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Abstract

Based on the provincial panel data of China spanning from 2010 to 2021, this paper employs fixed effects and mediation models to dissect the mechanism by which the development of green finance impacts carbon emission reduction. The results indicate that: (1) the development of green finance has an inhibitory effect on carbon intensity, meaning that the advancement of green finance can promote carbon emission reduction. This conclusion remains valid after robustness checks using instrumental variable methods and alternative dependent variables. (2) The impact of green finance development on carbon intensity exhibits regional heterogeneity, with the influence being particularly pronounced in western provinces and least evident in eastern regions. (3) Corporate green technological innovation and regional industrial structure upgrading play a partial mediating role in the effect of green finance development on carbon intensity. Therefore, it is recommended that local governments tailor their green finance development policies according to specific conditions, encourage enterprises to actively adopt green technological innovation measures to facilitate green transformation, thereby promoting industrial structure upgrades, and further unleash the potential of green finance to enhance the efficiency of carbon emission reduction.

Keywords Development of Green Finance; Carbon Intensity; Green Technological Innovation; Industrial Structure Upgrading

1 Introduction

To achieve the ambitious goals of peak carbon emissions and carbon neutrality, China is implementing a series of policy measures. These measures span multiple sectors, from optimizing the energy structure to transforming industrial structures, to the development of carbon emission trading markets and the establishment and implementation of trading systems; the gradual establishment of a green financial system, including the promotion of green credit, green securities, and green insurance policies; guiding financial institutions to invest in green projects, strengthening the regulatory guidance of green finance to direct capital flows, to fostering substantive technological innovations and optimizing industrial structures to promote green development, improve environmental quality, and enhance the environmental awareness of financial institutions... Each measure embodies China's resolve and responsibility in moving towards a green and low-carbon development path.

Green finance is an economic activity that supports environmental improvement, addresses climate change, and enhances resource utilization efficiency. It is a crucial tool for promoting green development and achieving harmonious coexistence between humans and nature. In recent years, China's green finance sector has experienced rapid growth, with the scale of green credit and the green bond market expanding annually, and the green insurance market developing steadily (Bi, 2024). However, there are significant

regional disparities, with the construction of the green finance network exhibiting a "dense east and sparse west" geographical distribution pattern. Only a few cities play a vital bridging role within the entire network (Li and Xiao, 2023). Spatially, carbon emission efficiency shows a "north-south divide" and "east high, west low" distribution, with the per capita carbon emissions and carbon emission efficiency in the east and west experiencing an "efficiency mismatch" (Sun and Liu, 2023).

Regarding the relationship between green finance and carbon emission reduction, scholars hold differing views. One perspective posits that digital finance may increase carbon emissions through consumption and employment effects (Deng and Zhang, 2021; Wang and Jiang, 2022; He and Yang , 2021). Another viewpoint argues that a well-functioning green finance system can, to some extent, curb carbon emissions. The mechanisms primarily involve enhancing carbon productivity and the proportion of clean energy consumption through economic growth, guiding funds toward technological innovation, regional innovation, technological progress, human capital, and marketization effects, promoting the rationalization and upgrading of industrial structures, and increasing credit allocation, thereby improving the ecological environment and reducing regional carbon emissions (Yao, 2021; Tan, 2023; Sun et al, 2017; Wen 2023; Zhou, 2023). There is also a view that suggests an inverted U-shaped relationship exists between green finance and carbon emission levels. For instance, Wang et al. (2022) argue that the broad coverage and deep usage of digital finance have a nonlinear impact on manufacturing carbon intensity, initially promoting increases before leading to reductions. Li (2023) notes that this inverted U-shaped relationship is more pronounced in central and western China compared to the eastern region.

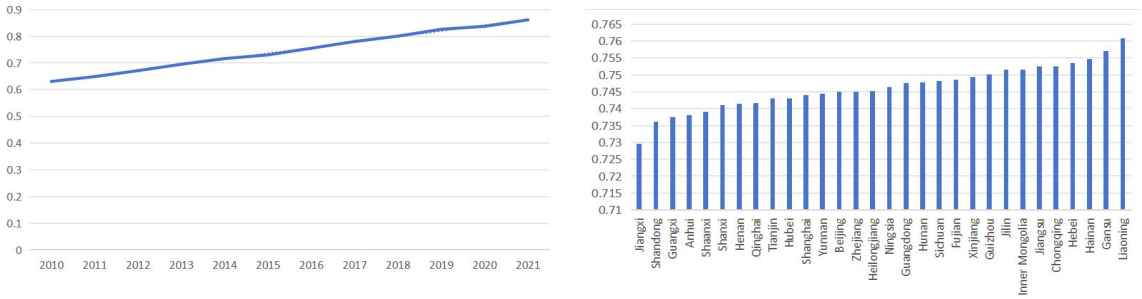
In summary, most studies on the carbon emission reduction effect of green finance conclude that green finance can reduce CO2 emission intensity. This paper analyzes the carbon emission reduction effect of green finance development from the perspectives of heterogeneity and transmission paths, aiming to reveal the actual operational rules of the carbon emission reduction effect of green finance development. This is intended to improve the carbon emission efficiency of enterprises in different regions, which is of great practical significance for alleviating the severe situation of global warming and achieving the "dual carbon" goals. Possible marginal contributions include the use of two core indicators—the green finance index and the carbon emission intensity index—and the introduction of green technological innovation level and industrial structure upgrading as mediating variables. This further explores how the development of green finance contributes to carbon emission reduction, making a marginal contribution to revealing the mechanism and pathways through which green finance development affects carbon emission reduction.

The subsequent sections of this paper are structured as follows: Section 2 discusses the current status of green finance and carbon emission reduction in China; Section 3 elaborates on the mechanism and pathways through which green finance development impacts carbon emission reduction, proposing research hypotheses; Section 4 presents the research design and model construction; Section 5 empirically analyzes the carbon emission reduction effect and transmission mechanisms of green finance development; and Section 6 provides research conclusions and Prospects.

2 Current Status of Green Finance and Carbon Emission Reduction in China

2.1 The Concept and Development Status of Green Finance

Green finance, as an innovative practice in the financial sector, is a critical tool for implementing green and low-carbon development strategies. It emphasizes the decisive role of the financial system in resource allocation and encourages financial institutions and enterprises to consider their social responsibilities. The core of green finance lies in promoting the sustainable use of resources through financial means, driving the green transformation of the economy and society, while ensuring the stable development of financial markets.



（a）Distribution over the years　　(b) Distribution of provinces

Fig. 1. Average values of green financial development index and the distribution of average values for each province over the years.
Data source : The authors obtained the data from various statistical yearbooks of China

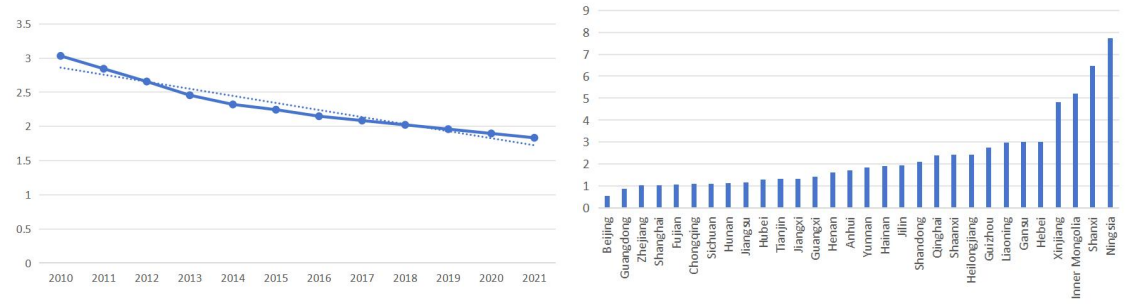
Green finance has undergone a process of initiation, rapid development, and maturation over the past decade, playing a significant role in promoting the green transformation of the economy and addressing climate change. As shown in Figure 1(a), China's green finance development index exhibited a steady upward trend from 2010 to 2021. With the growing global emphasis on sustainable development and climate change, it is anticipated that green finance will continue to maintain a strong momentum in the future.

As illustrated in Figure 1(b), the green finance development indices of various provinces in China from 2010 to 2021 demonstrated different levels of development, reflecting the efforts and achievements of each region in the field of green finance. This also highlights the uneven development of green finance across China. Such disparities may be associated with the economic development levels, policy support, and market acceptance in different regions. During the observation period, Jiangxi Province showed relatively lower levels of green finance development, whereas Liaoning Province exhibited higher levels. Generally, the financial systems in eastern regions are more developed, resulting in generally higher green finance development indices.

2.2 The Concept and Development Status of Carbon Emission Reduction

In the context of increasingly severe global climate change, governments and international organizations worldwide are seeking effective solutions. Among these, reducing greenhouse gas emissions, particularly carbon dioxide emissions, is considered one of the key measures to address climate change. Carbon emission intensity refers to the amount of CO2 emitted per unit of output in a specific economic activity or production process. This indicator is commonly used to measure the carbon intensity of economic activities, i.e., the extent to which carbon emissions can be reduced when producing the same quantity of goods or services compared to traditional methods. It directly reflects the efficiency of carbon resource utilization and environmental friendliness in the production processes of countries, regions, or enterprises.

In this paper, carbon emission intensity is measured by dividing the total carbon emissions by the regional GDP. This is an important indicator for assessing the environmental impact of economic activities. It not only reflects the current level of carbon emissions but also indicates the potential and direction for future emission reductions.



（a）Distribution over the years　　（b）Distribution of provinces

Fig. 2. The distribution of average carbon emission intensities and the average intensity values for each province over the years.
Data source: The authors obtained the data from various statistical yearbooks of China

The construction of a green financial system holds substantial significance in promoting the green transformation of China's economy and in coping with climate change. As illustrated in Figure 2(a), from 2010 to 2021, along with the growing awareness of carbon emission reduction within society and under the guidance of relevant policies, the carbon emission intensity in China witnessed a gradual decline. Subsequent to the State Council's initial proposal of "constructing a green financial system" in 2015, the carbon emission intensity in China leveled off, which serves as an indication of the strengthened awareness of green development among Chinese enterprises and the favorable outcomes of relevant policy guidance.

As depicted in Figure 2(b), marked differences exist in carbon emission intensity among different provinces, primarily stemming from the disparities in economic development levels, energy structures, and industrial structures across various regions. The provinces in the western region generally exhibit relatively high carbon emission intensities, which might be attributed to the abundant natural resources in these areas and their economic structures preponderantly composed of heavy industries. Xinjiang, Inner Mongolia, Shanxi, and Ningxia, being major energy-supplying provinces, possess far higher carbon emission intensities than the relatively developed cities in the eastern region. Beijing demonstrates a relatively low carbon emission intensity, which could be associated with its status as the nation's capital, entailing higher environmental protection standards and advanced technological applications. Moreover, Ningxia also has a relatively high carbon emission intensity owing to the large number of energy enterprises it hosts. Such regional differences, to a great extent, mirror China's economic development patterns and energy consumption habits, signifying that in order to attain the carbon emission reduction goals, China is required to implement differential energy conservation and emission reduction policies on a national scale and take corresponding actions at the local level.

3 The Mechanism Path and Research Hypothesis of Green Financial Development Affecting Carbon Emission Reduction

3.1 Relationship between Green Finance and Carbon Emission Reduction

The rise of green finance has a positive impact on reducing carbon emission intensity through the fundamental function of financial intermediation. Its mechanism of action is mainly reflected in the following aspects: First, the implementation of green finance policies conveys the demand for green investment to the market, demonstrating the government's firm commitment to developing a green economy. Such policy orientation helps guide enterprises and investors to pay attention to environmental protection and sustainable development, thereby reducing carbon emissions. Second, green finance provides necessary financial support for low-carbon projects, including services such as fund-raising and settlement, reducing the capital costs of these projects, enhancing their attractiveness and implementation efficiency, and contributing to the acceleration of the implementation of low-carbon projects, thereby reducing overall carbon emissions. In addition, with the development of green finance, related financial services are constantly improving, such as risk assessment and management and enhanced information transparency. The improvement of these services helps improve the feasibility and attractiveness of low-carbon projects and promotes the transformation of the green economy. In terms of the mechanism

directly acting on carbon emission efficiency, green finance functions through the signal transmission mechanism and the information disclosure mechanism. The signal transmission mechanism refers to the government's transmission of a support signal for the low-carbon economy to the market through green finance policies, while the information disclosure mechanism involves enterprises publicly disclosing their environmental impacts and carbon emission situations, increasing corporate transparency and prompting them to develop in a low-carbon direction. Therefore, the following hypothesis is proposed:

H1: The development of green finance can reduce carbon emission intensity and improve carbon emission efficiency.

3.2 Certain Heterogeneity in the Carbon Emission Reduction Effect of Green Finance Development

Green finance promotes investment in clean energy and renewable energy, improves energy efficiency, and drives the innovation of low-carbon technologies and products by providing financial support and risk management services, thus directly reducing greenhouse gas emissions. Green finance not only has a direct impact on carbon emissions in the local area but also can have a positive external effect on surrounding areas. This is because the environmental protection projects and technological improvements supported by green finance can not only reduce pollutant emissions but also improve resource utilization efficiency and promote sustainable development within the region, thereby having a positive impact on neighboring areas. Although green finance has direct and spatial spillover effects on carbon emission reduction, its impact may not be immediately apparent. The effect of carbon emission reduction may take some time to manifest, as the implementation and effect of green projects require time for observation and evaluation. In addition, changes in factors such as the marketization process of green finance, policy support, and public awareness may also affect its long-term effect on carbon emission reduction.

China has a vast territory, and there are significant regional differences in resources and economic development levels. The eastern region has a large number of large enterprises and a relatively developed financial industry, providing a favorable development environment for green finance. The financial system in the western region is relatively weak and it is difficult to form a complete financial system. The effect of green finance development on carbon emission efficiency may be less significant in the western region than in the eastern region. Since the green finance development policies of different provinces vary and environmental factors also differ significantly, the inter-provincial influence cannot be ignored. When some provinces in a region have a relatively high level of green finance development, they can also have a significant impact on the green finance development of neighboring provinces. This will lead to differences in the impact of green finance on carbon emission intensity. Therefore, the following hypothesis is proposed:

H2: There is certain regional heterogeneity in the impact of green finance development on carbon emission intensity.

3.3 The Mediating Effect of Corporate Green Innovation in Green Finance Improving Carbon Emission Efficiency

Green technological innovation covers multiple fields such as pollution control and prevention technologies, taking into account ecological principles and ecological economic laws, aiming to avoid, eliminate or reduce the pollution and damage to the ecological environment. With the gradual progress of green technological innovation, we can expect to see a profound ecological transformation. Such "non-polluting" or "less polluting" technological innovation is not only a key force in promoting green development but also an important means to achieve carbon emission reduction goals.

In the process of green technological innovation, as the main body of technological innovation, enterprises face challenges mainly including technical difficulties, cost-market acceptance, policy changes and resource integration. Green technological innovation usually requires large upfront investments. Whether in terms of talent support or technological R & D, enterprises need to conduct a large amount of financing, which undoubtedly increases the financial risk of enterprises. In addition, it also takes a certain amount of time and opportunity, as well as efforts in resource integration for the results of green technological innovation to be accepted by the market. To support green technological innovation, relevant policies and financial tools become particularly important. These policies and financial tools can not only directly provide financial support for enterprises but also, to a certain extent, disperse the financing risk of enterprises, provide enterprises with more flexible market information and

help enterprises better integrate resources. In addition, these policies and financial tools can also guide more enterprises to transform into green enterprises, accelerate the development and prosperity of green innovation technologies of various enterprises, achieve industrial upgrading and thus improve carbon emission efficiency.

In summary, green technological innovation has far-reaching and positive significance in promoting carbon emission reduction. It reduces carbon emission intensity by improving energy efficiency and promoting the development of clean energy technologies. At the same time, green technological innovation can also promote the green transformation of traditional industries. For example, by improving production processes and using environmentally friendly materials, it reduces the carbon footprint in the industrial production process. In addition, green technological innovation can also stimulate new business models and market demands, promote the efficient use and recycling of resources and further reduce carbon emissions. Therefore, green technological innovation plays an important role in addressing climate change and achieving sustainable development. Therefore, the following hypothesis is proposed:

H3: Green finance can improve carbon emission efficiency by promoting green technological innovation.

3.4 The mediating effect of industrial structure upgrading in green finance improving carbon emission efficiency

The overall upgrading of industrial structure refers to the transformation of a country or region from low value-added to high value-added industries, the evolution from labor-intensive to technology-intensive industries, and the upgrade from traditional industries to modern service industries and advanced manufacturing industries during the process of economic development through technological innovation, industrial transformation and optimal allocation. This process involves the elevation of industrial levels, the extension of industrial chains, the development of industrial clusters and the enhancement of industrial competitiveness, aiming to promote the improvement of the quality of economic development and sustainable development.

With the development of green finance, the industrial structure has been adjusted. Low energy consumption has become the mainstream direction of enterprise industrial transformation, and high-pollution industries have been reformed or phased out. The impacts of green finance on the primary, secondary and tertiary industries are also different. Therefore, a simple industrial structure adjustment cannot well reflect the existing degree of industrial change, so the overall upgrading of industrial structure has gradually become the mainstream of research. The upgrading of industrial structure is often accompanied by the formation of industrial clusters, which is conducive to the formation of economies of scale and helps to improve China's carbon emission efficiency to a large extent. Similarly, emerging industries or the early stage of industrial structure adjustment require a large amount of investment for infrastructure construction and product research and development, etc., and the financing brought about by the development of green finance can effectively solve this problem. In addition, the upgrading of industrial structure can effectively reduce the use of polluting energy such as coal and guide enterprises to use clean energy.

In summary, the upgrading of industrial structure can make full use of the market mechanism, starting from supply and demand, and effectively affect the distribution of enterprises and consumers' choices. And the transformation of different industries will also promote the clean energy revolution and further improve carbon emission efficiency. Therefore, the overall upgrading of industrial structure is of great significance for the achievement of the "dual Carbon" goals. Therefore, the following hypothesis is proposed:

H4: Green finance improves carbon emission efficiency by promoting the overall upgrading of industrial structure.

4 Research Design

4.1 Data Sources and Sample Selection

In this paper, panel data of 30 provinces (excluding Tibet, Taiwan, Macau, and Hong Kong) from 2010 to 2021 are selected as the research sample. The relevant data are obtained from various statistical yearbooks, and the missing data are retrieved from the databases of various social science surveys.

4.2 Data Sources and Sample Selection

This paper conducts a pooled OLS regression analysis using the panel data model. Subsequently, it compares the random effects regression (RE) and the fixed effects regression (FE) to preliminarily explore the basic relationships between the core explanatory variables and the explained variables. When determining the optimal model, the F-test and the Hausman test are used to evaluate the applicability of different models, thereby reducing the potential biases in the regression analysis and laying a solid research foundation for the subsequent mediation effect analysis. The details are as follows:

$$\mathrm{Carbon}_{it} = \alpha + \beta \mathrm{Green}_{it} + \gamma \mathrm{X}_{it} + \varepsilon_{it} \quad (1)$$

Where i represents province; t signifies year. The explained variable is carbon emission intensity (Carbon), which is impacted by multiple factors; the explanatory variable is green financial development index (Green). The present study refers to other literature, including energy structure (Energy), economic development level (Econo), environmental regulation (Envir), government intervention (Gover), and information development level (Infor) as control variables; ε_{it} is a random disturbance term.

Based on a mechanism study concerning digital finance's indirect influence over carbon abatement, this paper introduces green technology innovation along with industrial structure upgrading as intermediate variables. With reference to the mediator effect analysis method by Wen and Ye (2014), the following formulas are established:

$$\mathrm{Tec}h_{it} = \alpha_2 + \beta_2 \mathrm{Green}_{it} + \gamma_2 \mathrm{X}_{it} + \varepsilon_{it} \quad (2)$$

$$\mathrm{Carbon}_{it} = \alpha_3 + \beta_3 \mathrm{Green}_{it} + \delta \mathrm{Tec}h_{it} + \gamma_3 \mathrm{X}_{it} + \varepsilon_{it} \quad (3)$$

$$\mathrm{Industrial}_{it} = \alpha_2 + \beta_2 \mathrm{Green}_{it} + \gamma_2 \mathrm{X}_{it} + \varepsilon_{it} \quad (4)$$

$$\mathrm{Carbon}_{it} = \alpha_3 + \beta_3 \mathrm{Green}_{it} + \delta \mathrm{Industrial}_{it} + \gamma_3 \mathrm{X}_{it} + \varepsilon_{it} \quad (5)$$

Where i stands for province; t signifies year; ε_{it} is a random perturbation term. If the explained variable in (2) (4) is not significant to the mediating coefficient β_2, the explained variable has no effect on the mediating variable, and there is no mediating effect. If significant, then conduct experiments (3) and (5). In the empirical analysis of Model (3) (5), if the mediating variable coefficient δ is insignificant, it implies absence of mediator effect; on the contrary, there is a mediating effect. When there is a mediating effect, if the explanatory variable coefficient β_3 is significant, It demonstrates that green technological innovation or industrial structure upgrading only partially mediates the carbon emission reduction mechanism of green financial development; rather, it serves as a complete intermediate.

4.3 Variable Definition and Descriptive Statistics

(1) Dependent Variable: Carbon Emission Intensity (Carbon)

The carbon emission intensity is represented by dividing the carbon emissions by the GDP of the region.

(2) Independent Variable: Green Finance Development Index (Green)

The green finance development index is calculated by the entropy value method, which reflects the effect of capital allocation in the green finance market and the market liquidity, embodying the overall development situation of the market. This index includes indicators such as green credit and aims to guide resources to gather in industries related to green environmental protection and sustainable development. In this paper, the green finance development index will be used as the measurement result of the green finance development status of each province.

Table 1. Measurement of green financial development index

First-level Index	Second-level Index	Calculation Method
Green financial development index	Green credit	Environmental Protection Project Credit Ratio
	Green investment	The Proportion of Investment in Environmental Pollution Control to GDP
	Green insurance	Level of environmental contamination liability insurance promotion
	Green bond	Degree of Green Bond Development
	Green support	Percentage of budgetary environmental protection spending
	Green fund	Green Fund Proportion
	Green rights	Green rights and interests development depth

(3) Control variables

It mainly includes energy structure (Energy), economic development level (Econo), environmental regulation (Envir), government intervention (Gover), and information development level (Infor).

(4) Intermediary variables : green technology innovation level (Tech) and industrial structure upgrading (Industrial)

Table 2. Definitions of variables

Variable	Name	Symbol	Definition
Explained variables	Carbon emission intensity	Carbon	Total CO2 emissions/GDP
Core explanatory variables	Green financial development index	Green	See table 1.
Control variables	Energy structure	Energy	Regional / total national electricity consumption
	Informationization level	Infor	Total post and telecommunication business / regional GDP
	Economic growth level	Econo	Per Capita GDP
	Environmental regulation	Envir	Investment in industrial pollution control / industrial added value
	Government intervention degree	Gover	Regional GDP from fiscal spending
Mediator variable	Level of green technology innovation	Tech	Number of corporate green patent applications
	Ugrading of industrial structure	Industrial	Added value of primary industry as a share of GDP * 1 + added value of secondary industry as a share of GDP * 2 + added value of tertiary industry as a share of GDP * 3

The results of descriptive statistics for the variables are shown in Table 3. There are a total of 360 sample sizes in this panel data, and there are no missing values. Among them, the mean value of the main explanatory variable is 0.746, the median is 0.744, the standard deviation is 0.0760, the minimum value is 0.601, and the maximum value is 0.899. The mean value of the explained variable is 2.291, the median is 1.663, the standard deviation is 1.744, the minimum value is 0.319, and the maximum value is 8.519. It can be seen from the above data situation that both the explained variable and the explanatory variable have relatively large changes from 2010 to 2021, indicating that there are significant differences in carbon emission intensity among various regions.

Table 3. Descriptive statistics

Variables	Quantity	Average number	Median	standard deviation	Minimum value	Maximum value
Carbon	360	2. 291	1. 663	1. 744	0. 319	8. 519
Green	360	0. 746	0. 744	0. 076	0. 601	0. 899
Energy	360	0. 033	0. 026	0. 023	0. 004	0. 097
Envir	360	0. 003	0. 002	0. 003	0	0. 031
Gover	360	0. 246	0. 223	0. 102	0. 106	0. 643
Econo	360	9. 319	9. 199	0. 464	8. 467	10. 78
Infor	360	0. 062	0. 038	0. 053	0. 014	0. 290
Tech	360	7. 343	7. 395	1. 426	2. 565	10. 38
Industrial	360	2. 372	2. 362	0. 130	2. 127	2. 836

5 Empirical Results and Analysis

5.1 Analysis of the Direct Carbon Emission Reduction Effect of Green Finance

Before the empirical analysis, we still need to conduct a Hausman test to determine the model to be selected for this empirical part. According to the results of the Hausman test, the P-value is greater than zero, and the null hypothesis is rejected. Therefore, it can be judged that the fixed effect model is significant and superior to the random effect model.

Table 4. Empirical Analysis

	OLS	FE	RE
	Carbon	Carbon	Carbon
Green	-2.938***	-4.038***	-4.350***
	(1.058)	(0.312)	(0.330)
Energy	6.038	19.846***	9.461*
	(3.786)	(6.553)	(5.415)
Envir	243.476***	-20.729***	-17.232**
	(23.873)	(7.630)	(8.423)
Gover	3.179***	-1.296	0.730
	(1.010)	(0.963)	(0.932)
Econo	-0.522***	-1.857***	-1.323***
	(0.172)	(0.308)	(0.267)
Informatization	2.052	-0.706*	-0.705
	(1.594)	(0.416)	(0.462)
_cons	7.420***	22.381***	17.469***
	(1.801)	(2.910)	(2.544)
N	360	360	360
r2	0.391	0.571	
r2_a	0.381	0.524	

*Standard errors in parentheses； * p < 0.1, ** p < 0.05, *** p < 0.01*

As shown in Table 4, the R-squared of the FE model is 0.571, indicating that the fixed effect model has a good explanatory power. The corresponding coefficient of the green finance development index is -4.038, which is significantly negative at the 1% level. This shows that the development of green finance has a significant negative impact on carbon emission intensity, that is, the development of green finance can effectively promote the reduction of carbon emission intensity, or has a positive impact on the improvement of carbon emission efficiency. Thus, the conclusion of H1 is verified to be true.

From the results of the control variables, the impact of energy structure (Energy) on carbon emission intensity is positive. That is, the higher the electricity consumption in the region, the higher the carbon emission intensity. This is due to the fact that coal is the main energy source for electricity in China at the present stage. The result of environmental regulation (Environmental) on carbon emission intensity is negative, indicating that the higher the investment in pollution control, the lower the carbon emission

intensity in the region.

(1) Endogenous test

In the relationship between green finance and carbon emission efficiency, the development of green finance has a certain impact on the improvement of carbon emission efficiency, and it is also possible that the improvement of carbon emission efficiency forces the development of green finance. To address this causal relationship, following the approach of Pan et al. (2024), this paper takes the lagged first-order of the green finance development index as an instrumental variable and conducts a two-stage least squares estimation for the endogeneity test. As can be seen from the experimental results in Table 5, the estimated coefficient of green finance development is -4.347, which passes the test at the 1% significance level, indicating that the model has a certain degree of stability and that the development of green finance promotes the improvement of carbon emission efficiency.

Table 5. Endogenous test of instrumental variables

	The first stage	**The second stage**
	Carbon	Carbon
L. Green	0.873***	
	(0.031)	
Green		-4.347***
		(0.370)
Energy	-0.873	15.954**
	(0.679)	(7.082)
Envir	-1.058	-30.739***
	(0.714)	(7.538)
Gover	0.110	0.596
	(0.106)	(1.116)
Econo	0.039	-1.220***
	(0.033)	(0.351)
Infor	0.033	-1.022**
	(0.042)	(0.446)
N	330	330
Centered R^2	0.8272	0.5145
F Anderson canon.corr.LR Statistic Cragg-Donald F statistic	234.56 392.654 794.359	50.65

Standard errors in parentheses； $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

(2) Robustness test

Here, we conduct a robustness test on this model by replacing the explained variable. Drawing on the method of constructing the non-radial and non-angular SBM model proposed by Yao (2021) and referring to the research results of Han Jun and Niu (2023), we utilize the super-efficiency SBM model to evaluate the carbon emission efficiency of provinces. The carbon emission intensity, which was originally used as the explained variable for measuring carbon emission efficiency, is replaced with the carbon emission efficiency calculated by the SBM model. Due to the delay in data update, the sample under the SBM model measurement is the provincial panel data from 2010 to 2019. At this time, since the explained variable is carbon emission efficiency, when the development of green finance deepens, the carbon emission efficiency should increase, so the result should be significantly positive.

As can be seen from the experimental results in Table 6, the estimated coefficients of green finance development have passed the test at the 1% significance level in the OLS regression model, the FE regression model, and the RE regression model, and all the coefficients are positive, which is consistent with the predicted results. Among them, the coefficient of the fixed effect model is 0.605, indicating that the model has a certain degree of stability and that the development of green finance promotes the improvement of carbon emission efficiency.

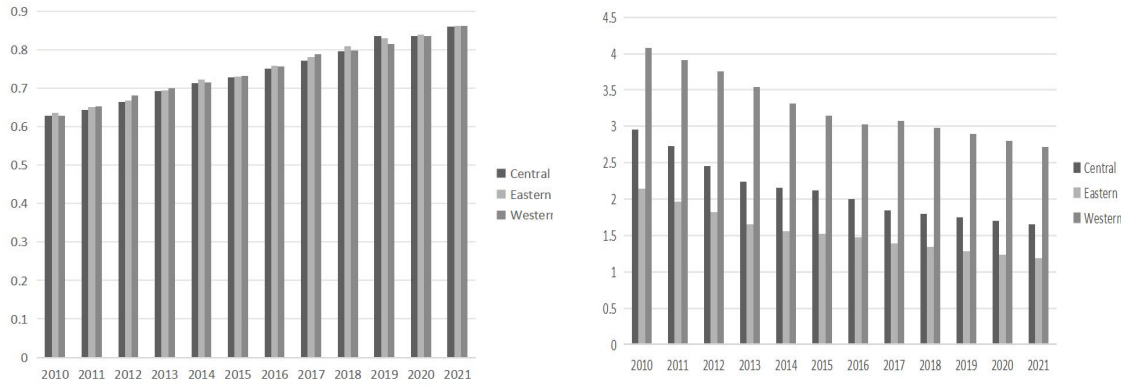
Table 6. Replacement of explanatory variables robustness test

	OLS	FE	RE
	Efficiency	Efficiency	Efficiency
Green	0.341***	0.605***	0.484***
	(0.120)	(0.113)	(0.091)
Energy	0.039	-1.517	-0.643
	(0.365)	(1.820)	(0.763)
Envir	-2.829	-3.355*	-3.067
	(2.175)	(1.954)	(1.902)
Gover	0.041	-0.638**	-0.190
	(0.097)	(0.307)	(0.173)
Econo	0.104***	0.035	0.095***
	(0.016)	(0.086)	(0.037)
Infor	0.151	-0.030	0.038
	(0.207)	(0.153)	(0.148)
_cons	-0.367**	0.317	-0.292
	(0.174)	(0.807)	(0.349)
N	300	300	300
r2	0.183	0.181	
r2_a	0.166	0.072	

Standard errors in parentheses； $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

5.2 Heterogeneity Analysis of Carbon Emission Reduction Effect of Green Finance

This paper follows the approach of Li (2023) to divide the samples into three major regions: the eastern, central, and western regions. The development of green finance and the situation of carbon emission efficiency in each region are as follows.



（a）Regional distribution of green finance （b）Regional distribution of carbon

Fig. 3. Green financial development index and regional distribution map of carbon emission intensity
Data source : The authors obtained the data from various statistical yearbooks of China

As shown in Figure 3(a), the green finance development indices in the eastern, central, and western regions have all steadily increased from 2010 to 2021. Among them, the level of green finance development in the eastern region was only lower than that in the western region from 2012 to 2013, and has otherwise been at the top among the three regions, which is related to the developed financial system in the eastern region. As can be seen from Figure 3(b), the carbon emission intensities in each region have shown a downward trend. The main reason is that the policies related to carbon emission reduction have been implemented in recent years, and the decline in carbon emission intensity is considerable. However, the carbon emission intensity in the western region has always been the highest, which is closely related to factors such as the local energy structure.

Through the region-by-region test using the fixed effect model, the results are shown in Table 7. The impact of the green finance development index on carbon emission intensity is significantly negative in the eastern, central, and western regions of China, indicating that the development of green finance can

reduce the carbon emission intensity in each region, but there are still differences in specific regions. The coefficient of the explanatory variable in the eastern region is -2.819. Compared with -4.405 in the central region and -4.853 in the western region, the impact of green finance development in the eastern region on the reduction of carbon emission intensity is relatively lower. There is heterogeneity in the impact of green finance development on the reduction of carbon emission intensity. The development of the financial industry and industry in the eastern provinces is significantly higher than that in the other two regions, which is somewhat inconsistent with H2. This is mainly because the differences in industrial bases and development models among different regions will affect the degree of coupling between economic growth and green finance development policies. In the highly developed eastern region, since polluting enterprises can obtain financing from many other channels, simply relying on the existing green finance-related policies is difficult to further release the potential of green finance, and there may be an upper limit of policy incentives. The impact coefficient in the western region is higher than that in other regions. The possible reason is that its financial development started relatively late. Compared with the transformation of traditional industries, the direct development speed of the green finance industry is relatively fast. Polluting enterprises mostly meet the financing standards of financial institutions to obtain corresponding financing. Therefore, the effect of reducing carbon emissions by the development of green finance in this region is obvious, that is, the effect of promoting the improvement of carbon emission efficiency is relatively low.

Table 7. Heterogeneity analysis

	nationwide	Eastern	Central	Western
	Carbon	Carbon	Carbon	Carbon
Green	-4.038***	-2.819***	-4.405***	-4.853***
	(0.312)	(0.264)	(0.350)	(0.789)
Energy	19.846***	6.208	22.928**	35.231**
	(6.553)	(5.359)	(10.935)	(14.872)
Envir	-20.729***	-3.349	-33.129**	-24.232*
	(7.630)	(8.810)	(16.213)	(12.506)
Gover	-1.296	-4.450***	-3.694***	-1.599
	(0.963)	(0.961)	(1.126)	(2.018)
Econo	-1.857***	-0.922***	-1.488***	-4.151***
	(0.308)	(0.220)	(0.374)	(0.774)
Infor	-0.706*	0.519	0.913*	-1.171
	(0.416)	(0.433)	(0.529)	(0.755)
_cons	22.381***	13.176***	19.185***	44.185***
	(2.910)	(2.173)	(3.431)	(7.164)
N	360	132	108	120
r2	0.571	0.772	0.826	0.581
r2_a	0.524	0.740	0.800	0.521

*Standard errors in parentheses； * p < 0.1, ** p < 0.05, *** p < 0.01*

5.3 Analysis of the Mediating Effect of Enterprise Green Technology Innovation

As shown in Table 8, after adding the mediating variables, the coefficient of green finance development is -3.105, and the coefficient of green technological innovation is -0.164. This indicates that green technological innovation plays a partial mediating role in the process where green finance development suppresses carbon emission intensity. That is, the development of green finance can reduce the carbon emission intensity of enterprises by promoting their green technological innovation. This result verifies that the conclusion of Hypothesis Three is true. The main reasons are as follows: The development of green finance guides the flow of funds and supports green technological innovation. Meanwhile, the relevant policies introduced and the specific demands of the market for green innovative technologies are reflected to the relevant enterprises, and risks are also shared for enterprises during the process of technological upgrading and the development and sales of products. Under the dual effects of financial support and incentive guidance, the carbon emission efficiency of enterprises is improved.

Table 8. Mediating effect of green technology innovation

	(2)	(3)	(4)
	Carbon	Tech	Carbon
Green	-4.038***	5.700***	-3.105***
	(0.312)	(0.374)	(0.401)
Energy	19.846***	8.286	21.202***
	(6.553)	(7.869)	(6.446)
Envir	-20.729***	16.193*	-18.079**
	(7.630)	(9.162)	(7.529)
Gover	-1.296	7.965***	0.007
	(0.963)	(1.156)	(1.013)
Econo	-1.857***	1.820***	-1.559***
	(0.308)	(0.369)	(0.313)
Infor	-0.706*	0.697	-0.592
	(0.416)	(0.499)	(0.410)
Tech			-0.164***
			(0.045)
_cons	22.381***	-16.207***	19.728***
	(2.910)	(3.494)	(2.951)
N	360	360	360
r2	0.571	0.676	0.587
r2_a	0.524	0.641	0.541

Standard errors in parentheses； $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$*

As shown in Table 9, after adding the industrial structure upgrading as the mediating variable, the model is significant. The coefficient of green finance development is -3.232, and the coefficient of industrial structure upgrading is -1.139. This indicates that industrial structure upgrading plays a partial mediating role in the process where green finance development suppresses carbon emission intensity. That is, the development of green finance can reduce the carbon emission intensity by promoting the upgrading of industrial structure. This result verifies that the conclusion of Hypothesis Four is true. The main reasons are that the upgrading of industrial structure affects the allocation of market resources, guides the transformation of energy used by enterprises, and promotes the reduction of carbon emission intensity in China. Green finance helps the upgrading of industrial structure, promotes the clean transformation of industries, and thus improves the carbon emission efficiency.

Table 9. The mediating effect of industrial structure upgrading

	(5)	(6)	(7)
	Carbon	Industrial	Carbon
Green	-4.038***	0.708***	-3.232***
	(0.312)	(0.029)	(0.522)
Energy	19.846***	0.391	20.292***
	(6.553)	(0.612)	(6.530)
Envir	-20.729***	0.891	-19.714**
	(7.630)	(0.713)	(7.617)
Gover	-1.296	0.119	-1.161
	(0.963)	(0.090)	(0.962)
Econo	-1.857***	-0.042	-1.905***
	(0.308)	(0.029)	(0.307)
Infor	-0.706*	0.142***	-0.545
	(0.416)	(0.039)	(0.423)
Industrial			-1.139*
			(0.592)
_cons	22.381***	2.185***	24.870***
	(2.910)	(0.272)	(3.173)
N	360	360	360
r2	0.571	0.782	0.576
r2_a	0.524	0.759	0.528

Standard errors in parentheses； $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

6 Research Conclusions and Prospects

This paper analyzes the mechanism and path of how green finance development affects carbon emission reduction based on the provincial panel data of China from 2010 to 2021, by introducing fixed effects and mediation effect models. The conclusions are as follows: (1) The development of green finance can promote the reduction of carbon emission intensity. Green finance promotes the green transformation of enterprises by guiding the flow of funds through policies and actively transmitting market signals, thereby reducing the carbon emission intensity of each province and gradually implementing the "dual carbon" goals. (2) The impact of green finance development on carbon emission intensity has a lag. Experiments show that the impact of green finance development on carbon emission reduction is continuous and increases with the increase of the lag period. This lag may be due to the fact that it takes a certain amount of time for the returns of green financial products to be realized in the market. (3) The impact of green finance development on carbon emission intensity is heterogeneous. The reason why the significance in the eastern region is weaker than that in the other two regions is that there is an upper limit to the incentive of green finance policies in this region; in the western region, the process of enterprise development into green finance-related enterprises has been relatively fast in the past decade, and the proportion of the increase in carbon emission intensity caused by green finance is relatively large, so the overall effect is the most significant. (4) Corporate green innovation technology and industrial structure upgrading have a partial mediating effect in the impact of green finance development on carbon emission intensity. The carbon emission reduction mechanism and path of green finance development still need to be explored, and the overall regulation of China's industrial upgrading can also be carried out to further improve the carbon emission efficiency of enterprises.

Although this study has achieved certain results in the analysis of the relationship between green finance development and carbon emission reduction, there are still some deficiencies. Firstly, in terms of data, although provincial panel data is used, there are certain difficulties in obtaining some data, resulting in the measurement of some indicators may not be accurate enough. For example, the construction of the green finance development index may not fully cover all relevant factors, which affects the accuracy of the research conclusions to a certain extent. Secondly, in terms of model setting, although fixed effects and mediation effect models are considered, there may be other factors that have not been considered affecting the accuracy of the model, such as the coordinated development effect between regions.

In view of the above deficiencies, future research can be carried out from the following directions. First, further improve the data collection channels, expand the data sources, and build a more

comprehensive and accurate index system to measure the level of green finance development and carbon emissions more accurately. Second, explore more complex model settings and incorporate more influencing factors to analyze the complex relationship between green finance development and carbon emission reduction more deeply. Third, study the coordinated effect of green finance development and industrial structure adjustment from a more microscopic perspective, and how to achieve the optimal allocation of green finance resources among regions through policy guidance, so as to promote the realization of carbon emission reduction goals more effectively.

Conflicts of Interest

The authors declare no conflicts of interest.

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