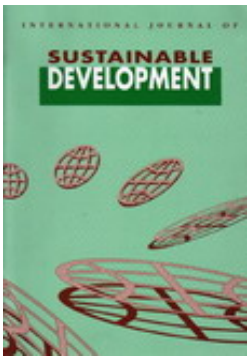

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Digital innovations and green finance: accelerating carbon neutrality in enterprise sustainability

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Abstract: Green finance (GF) is a pivotal driver for enhancing carbon-neutrality, ultimately fostering the sustainable development of enterprises. Drawing upon provincial panel data spanning 2007 to 2017, this study examines the impact of GF on carbon-neutrality and its mechanisms. The empirical findings highlight GF's significant positive influence on achieving carbon-neutral goals, a relationship that withstands varying research methodologies. This analysis uncovers disparities in GF's effectiveness in attaining these objectives, as well as spatial spillover effects. Notably, GF's promotion of carbon-neutral goals follows a nonlinear pattern, emphasising the complexity of the relationship. Additionally, green innovation emerges as a mediating force within the GF-driven process of carbon neutralisation (CN). These conclusions hold important policy implications for expediting CN realisation and improving global climate conditions, ultimately contributing to the sustainable development of enterprises.

Keyword: GF; CN; carbon-emission; green-development.

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1 Introduction

The rapid pace of industrialisation across nations has led to an alarming surge in environmental issues, notably air, water, soil, and light pollution. Moreover, the escalating global climate change and the looming spectre of global warming have intensified concerns. Presently, the soaring global carbon emissions pose a dire threat to human life's safety. Responding to the United Nations' call, China has taken a proactive stance in shouldering responsibility for combating global climate challenges. China has steadfastly advocated a trajectory of green, low-carbon, and high-quality development in tackling climate change, articulating a two-step approach aimed at achieving carbon peak and carbon neutrality. This commitment serves as a potent political impetus in combatting the greenhouse effect. Since the formulation of these goals, China has underscored the implementation strategies and paramount importance of carbon emission reduction in pivotal policy forums. The '14th five-year plan' outlines a comprehensive action blueprint, emphasising the gradual reduction of carbon emissions, bolstering the construction of ecological civilisation, propelling the energy revolution, establishing low-carbon cities, and steadfastly working toward the goal of carbon neutrality. China has exhibited unwavering confidence and a resolute sense of purpose in its pursuit of carbon reduction targets. The clarion call for carbon neutrality has evoked an enthusiastic response across various sectors, with diverse segments of society actively heeding the state's summons.

Green finance (GF) refers to a multifaceted approach within the financial sector that integrates environmental considerations into various aspects of investment, policy, and financial instruments. It encompasses a spectrum of strategies, frameworks, and tools designed to support environmentally sustainable economic activities and address climate-related challenges. Financial instruments within the realm of GF include specialised products like green bonds, which raise funds specifically for environmentally beneficial projects, as well as green loans, sustainability-linked loans, and other financial tools designed to support eco-friendly initiatives. These instruments often come with specific criteria or certifications ensuring the funds are allocated toward projects with positive environmental impacts. Overall, the concept of GF is dynamic and evolving, encompassing a broad spectrum of strategies, policies, and financial mechanisms aimed at fostering sustainable development, mitigating climate change, and preserving natural resources while delivering financial returns.

Since China's economy has entered the new stage, the relevant departments has attached great significance to green-development, which has constantly inspired the whole people to pursue green production and lifestyle. With the transformation of economic development mode and the optimisation of industrial structure, more and more people have paid attention to the vision of 'turning from virtual to real'. The financial industry no longer allows 'speculation with money', but focuses on promoting the development of the real economy. As a result, many green-financial instruments have been developed vigorously, which is a heavy means for the financial industry to reverse the development trend of 'get rid of reality to deficiency', known by more and more public. GF is trying to reverse the trend of environmental pollution and climate deterioration with its own advantages. The development process of GF in China can be traced back to the 1980s. Although it has a long history, the process is relatively slow. Until 2012, when the economy entered the stage of 'de-industrialisation', China's GF began to flourish. Its connotation and extension are constantly rich, and various green-financial instruments such as green credit and green bonds are gradually launched. So far, GF has been placed in an important strategic position of national development. The '14th five-year plan' once again clearly proposed to vigorously develop GF and build a green-development policy system. Whether in theory or in practice, GF plays an irreplaceable role in achieving the goal of CN. Nowadays, China is very optimistic about the favourable side of GF for carbon-emission reduction, and all sectors of society pay close attention to the important driving force of GF to carbon-neutral goal. Based on the current state of economic development in China, we cannot help but wonder whether GF in China can really help reduce carbon-emissions, and what is the mechanism? In order to clarify this problem thoroughly, we need to carry out in-depth theoretical and empirical analysis. The rapid development of global industrialisation will inevitably lead to climate deterioration and environmental pollution, and the development of GF is the inevitable choice to reduce the adverse effects of industrialisation. This paper will focus on the realisation of carbon-neutral goal, take GF as the breakthrough point, link financial development with ecological development, and provide scientific and operable theoretical guidance for the realisation of the long-term goal on the '14th five-year plan'.

In the rare studies on the relationship between GF and carbon-neutral goal, most of them adopt the method of theoretical analysis, and rarely carry out empirical test, which may lead to the deviation of research conclusions. Based on the existing literature, this paper analyses the data of GF and carbon-emissions, and explains the role of GF in achieving CN through empirical tests, which can greatly increase the reliability of the

research conclusions. Second, in the current research, most of the literature only focuses on the direct relationship between GF and carbon-neutral goal, and does not analyse the mechanism between the two. This paper proposes that green-innovation is the mechanism of GF affecting carbon-neutral goal, and the mechanism is affected by industrial structure. It is helpful to understand the relationship between GF and carbon-neutral goal more systematically.

The next arrangement of this paper is as follows: the second section reviews the literature around GF and carbon-neutral goal, the third section expounds the impact of GF on carbon-neutral goal through theoretical analysis, the fourth section is model design, the fifth section is empirical results and analysis, and the sixth section is research conclusions and policy recommendations.

2 Literature review

In recent years, both GF and carbon-neutral goals have become the focus of academic research. GF is an important driving force to accelerate the realisation of green-development and industrial structure optimisation in China, and also an important means to achieve the goal of CN as soon as possible. This paper will review the relevant literature from the perspective of GF, carbon-neutral goals and the relationship between them.

First of all, a large number of groups have studied GF. In the existing research on GF, most of them focus on the impact of GF: first, they focus on the macro-economic development, and think that GF can promote green-development (Cowan, 1998; Labatt and White, 2002; Shubik, 1975) and high-quality economic development (Zhou et al., 2020; Yang et al., 2021; Li et al., 2022a).The second is to focus on the meso level of the industry, believing that GF can effectively regulate funds, reduce funds flowing to polluting industries and increase funds, so as to optimise the industrial structure (Salazar, 1998; Li et al., 2022b; Zhu, 2022; Guo et al., 2023). Zhang et al. (2023) proposed that GF can adjust the energy structure, thus promoting the transformation of economic structure. Third, focusing on the micro level of enterprise development, GF is conducive to promoting enterprise financing and promoting green-innovation (Wang et al., 2016; Yang et al., 2021). These studies have laid a solid foundation for in-depth analysis of the role of GF in reducing carbon-emissions.

Secondly, more and more studies take carbon-neutral goal as the research background to calculate and study carbon-emissions. Some scholars focus on the provincial level (Wang et al., 2018), others focus on the municipal level (Wang et al., 2020), and others focus on the county-level carbon-emissions (Long et al., 2021). Many studies have pointed out that China's current carbon-emissions have a large space for decline. Regional studies have found that the carbon-emissions between the eastern and western regions show different characteristics. The eastern developed areas become the transfer out areas of carbon-emissions, while the less developed areas in the central and western regions gradually become the transfer places of carbon-emissions (Sun et al., 2016). It is necessary to avoid direct transfer of high emission industries (Guo et al., 2012). In addition, there are many published studies on the influencing factors of carbon-emissions, including economic and political perspectives, including digital economy (Pu et al., 2020), officials' exchange in different places (Zhu and Yang, 2023), urbanisation, technological progress (Ge, 2022), etc.

Finally, in recent years, many scholars began to link GF with carbon-neutral goal, and studied the impact of GF on carbon-neutral goal. Lv et al. (2021) believed that GF could participate in the process of environmental governance. Qin et al. (2022) believed that GF could helped enterprises obtained sufficient financing in the process of emission reduction, and reduced the uncertainty of enterprise emission reduction on development. Lan et al. (2023) believed that GF could curbed environmental pollution. Akan (2023) believed that GF could reduced carbon-emissions, and the energy structure adjustment played a conductive role, while the industrial structure adjustment played a regulating role in the conduction effect. However, Chen and Chen (2021) thought that the current financial system did not play a restrictive role in carbon-emissions, because of the lack of GF system. In the existing literature, most of them only qualitatively analyse the relationship between GF and carbon-neutral goal (Wang et al., 2022), but seldom do quantitative research. Moreover, few papers study the transmission mechanism between GF and carbon-neutral goal, which provides the idea for this paper.

3 Theoretical analysis and hypothesis raising

Specifically speaking, GF is guided by green-development and ecological civilisation. It is committed to providing various financial support for environmental protection and science-technology industries, regulating the flow of funds between different industries, and encouraging the development of green industries, so as to optimise the industrial structure to a certain extent.

The goal of green-financial structure can be achieved through the optimisation of carbon industry structure. In the process of continuously promoting the goal of CN, GF can use carbon-emission trading and other financial instruments to adjust the unreasonable part of the existing industrial structure, increase the proportion of low-carbon, energy-saving, green, environmental protection and other industries in the economic system, and reduce the proportion of high-energy-consuming industries.GF regards green-development as an important evaluation index of enterprise financing to decide whether to grant credit to relevant enterprises. Generally, GF tends to provide financing support for green environmental protection industries such as high-tech, which can effectively regulate the direction of capital flow and encourage the transfer of high-energy consumption industries to green environmental protection industries. In addition, GF can also promote the construction of green infrastructure, improve the coverage of GF and strengthen the influence of GF. In a word, GF directly promotes the development of low energy consumption industry and indirectly promotes the realisation of carbon-neutral goal through reasonable allocation of funds.

For enterprises that want to change from high energy consumption to low energy consumption, there are many challenges in the process of transformation, such as financing constraints. In order to encourage the transformation of enterprises, GF can improve the financing environment of enterprises, help enterprises reduce financing constraints, and promote the transformation and upgrading of enterprises to green environmental protection industry. Specifically, when enterprises take transformation measures to reduce carbon-emissions, they can release financing signals to GF and seek financing support from GF. GF participating in the transformation and upgrading of enterprises, on the one hand, can reduce the transformation cost of enterprises, because

GF usually gives enterprises preferential interest, on the other hand, it can reduce the risk of enterprise transformation, because GF bears part of the risk.

GF can also promote CN by endorsing low energy consumption industries. In the traditional market, there is a serious problem of information asymmetry between producers and consumers. Compared with producers, consumers tend to belong to vulnerable groups. It is difficult for them to assess which products in the market are low-carbon products and which are not. GF plays a very important role in this process. We can set a series of institutional guidelines, clearly judge low-carbon products, through various financial means, signal to consumers, reduce the degree of information asymmetry between consumers and producers, so as to improve the market share of low-carbon products and accelerate carbon-emission reduction. Based on the above analysis, we propose Hypothesis 1.

Hypothesis 1 GF can promote CN.

As we all know, environmental pollution has spatial aggregation effect, and it is easy to have mutual influence between regions. Theoretically speaking, the worse the environmental quality of a place, the more likely it is to lead to environmental deterioration in the surrounding areas. For example, after the upstream river is polluted, the water quality in the downstream area will also deteriorate. For example, if the air in a certain place is polluted, the air in the surrounding area will also be polluted due to the atmospheric fluidity. Because the mobility of air is inevitable, and at present, China has put carbon-emissions in an important national strategic position. Local governments are strictly supervised by the central government in carbon reduction actions. In order to obtain the approval of the central government, all localities will actively fall into competition and reduce carbon-emissions one after another. In addition, as the financial markets between regions are interconnected, local GF will also affect carbon-emissions in other regions. Based on the above analysis, we propose Hypothesis 2.

Hypothesis 2 The impact of GF on carbon-neutral goal has spatial spillover.

Although the beneficial impact of GF on carbon-neutral goal is obvious to all, the relationship between them is not necessarily a simple linear relationship. Even if there are differences between the two financial environment and environmental factors, there are likely to be differences between them. The impact of GF on carbon-neutral goal is likely to change with the influence of relevant factors. Based on the above analysis, we propose Hypothesis 3.

Hypothesis 3 The impact of GF on carbon-neutral goal may be nonlinear.

In theory, GF can really promote the realisation of carbon-neutral goal. So, what is the mechanism? This paper believes that one of the main functions of GF is to promote green-innovation of enterprises. Whether by optimising the financing structure or industrial structure, the purpose is the development of high-tech enterprises or encourage others to make green transformation, and improve the overall innovation ability of enterprises, as well as the improvement of green-innovation level can effectively reduction, so that can promote the realisation of carbon-neutral goal. In addition, it is well known that the impact of GF on carbon-neutral goal may be affected by industrial structure. Existing studies have pointed out that GF can adjust the industrial structure and promote the reduction of carbon-emissions. Therefore, the optimisation of industrial

structure can play an intermediary role in the impact of GF on carbon-neutral goal. Based on the above analysis, we propose Hypothesis 4 and Hypothesis 5.

Hypothesis 4 GF promotes CN by improving green-innovation.

Hypothesis 5 GF promotes CN by adjusting industrial structure.

4 Empirical design

4.1 Model design

The investigation utilises a regression model referred to as a two-way fixed effect model within the benchmark analysis, as delineated in equation (1). Herein, the variable denoted by C pertains to carbon emissions, serving as the primary explanatory factor within the scope of this paper's examination. GF is the main explanatory variable of this paper, and X is a series of control variables, and represents time fixed effect and individual fixed effect respectively.

$$C_{\mathrm{it}} = \alpha_0 + \alpha_1 GF_{it} + \theta X_{\mathrm{it}} + \lambda_t + \eta_i + \varepsilon_{\mathrm{it}} \tag{1}$$

4.2 Variable selection

Referring to the existing research, this paper constructs green-financial indicators from four angles, and uses entropy weight method to measure: first, green credit, which is measured by interest expenditure of high energy consuming industries; The second is green investment, which is measured by environmental pollution control investment; The third is green insurance, which is measured by agricultural insurance income; The last is financial support, which is measured by environmental protection expenditure.

The explained variable is carbon-neutral goal. In this paper, carbon-emissions are used as surrogate variables. The lower the carbon-emissions, the easier it is to achieve the carbon-neutral goal. In this paper, investment in fixed assets (INV) is used to express the fixed assets and social assets; urbanisation (URB) is represented by the proportion of urban population to the total population at the end of the year; industrial structure (IND) is expressed by the proportion of the added value of the primary industry in GDP; fiscal decentralisation (FDUR) is expressed by the proportion of fiscal revenue and expenditure; the unemployment rate (UNE);tax level (tax), expressed by the proportion of tax revenue and GDP; foreign investment (FDI) is expressed by the proportion of the actual use amount of foreign investment and GDP; the degree of opening up (OPEN) is expressed by the proportion of total import and export to GDP.

The intermediary variable is green-innovation. This paper uses the ratio of green patent application authorisation to patent application authorisation.

4.3 Data sources

The paper extracts data from the period spanning 2007 to 2017. Owing to the incomplete dataset pertaining to Tibet, information from 30 provinces (excluding Tibet) sourced from the China Statistical Yearbook, China Insurance Yearbook, China Financial

Yearbook, China Energy Statistical Yearbook, and CEARs database is utilised. Table 1 presents the descriptive statistics for each variable examined.

Table 1 Descriptive statistics

Variable	*Obs.*	*Mean*	*Std. dev.*	*Min*	*Max*
C	330	285.4071	180.4035	19.40624	768.3882
GF	330	0.1541873	0.0913899	0.0556	0.7588
INV	330	0.725954	0.2324198	0.2397517	1.469483
FDI	330	244.2918	241.3734	3.834835	1620.348
IND	330	10.62556	5.495127	0.36	30
FSUR	330	51.44738	19.64618	14.82647	95.08636
UNE	330	3.455152	0.6493687	1.2	4.6
TAX	330	7.982943	3.030651	4.03239	19.96511
URB	330	0.5407388	0.1348636	0.2822967	0.8960662
OPEN	330	3027.115	3,645.809	167.5874	18003.49

5 Empirical analysis

5.1 Benchmark regression analysis

Table 2 shows the test results of GF on carbon-emissions. In column (1), only the main explanatory variable of GF is added, and no control variable is controlled. The two-way fixed effect model is used. The regression results show that GF can significantly reduce the level of carbon-emissions, which is significant at the 1% level. Column (2) controls all the control variables and uses the fixed effect model. The regression results show that GF reduces carbon-emissions at the 1% level. Column (3) also controls all control variables, using a two-way fixed effect model. The regression results show that GF still reduces carbon-emissions at the 1% level. The results of benchmark regression preliminarily prove that GF can promote carbon-neutral goal. By means of benchmark regression, we prove hypothesis 1.

Table 2 Benchmark regression results

Variable	*(1)*	*(2)*	*(3)*
	C	*C*	*C*
GF	–250.246***	–352.598***	–333.927***
	(–4.39)	(–4.36)	(–4.41)
INV		–34.387**	–1.941
		(–2.07)	(–0.13)
FDI		0.013	0.022*
		(0.98)	(1.95)
IND		–0.948	–1.572
		(–0.61)	(–1.10)

Table 2 Benchmark regression results (continued)

Variable	*(1)*	*(2)*	*(3)*
	C	*C*	*C*
FSUR		0.106	–0.043
		(0.19)	(–0.07)
UNE		5.871	12.590**
		(0.79)	(1.99)
TAX		10.581***	–3.105
		(4.24)	(–1.15)
URB		953.631***	600.279***
		(11.43)	(5.42)
OPEN		–0.010***	–0.009***
		(–4.14)	(–3.89)
_cons	241.738***	–223.162***	–12.581
	(31.93)	(–3.35)	(–0.17)
Fixed time	Y	N	Y
Individual fixation	Y	Y	Y
N	330	330	330
R^2	0.661	0.584	0.712

5.2 Robustness test

5.2.1 Instrumental variable method

In theory, some studies have pointed out that carbon-emissions have forced the rapid development of GF, so there may be endogeneity between GF and carbon-emissions, which will have adverse impact on the research results. Based on this, this paper will use instrumental variable to eliminate the influence of endogeneity. When selecting the instrumental variables of GF, this paper uses the lagged second order of GF as the instrumental variables, which can better meet the exogenous assumption. The regression results are shown in Table 3 (1), which shows the second stage regression results of instrumental variable method. The results show that the impact of GF on carbon-emissions is indeed positive. Both weak identification test and non-recognition test show that the model is reasonable.

5.2.2 GMM test

In addition to the instrumental variable for endogenous test, this paper also uses GMM for regression test. Table 3 (2) shows the regression results of System GMM and differential GMM. The regression results show that the positive impact of GF on carbon-emissions is significant at the 5% level. In addition, the p value of AR (1) is less than 0.01, and the p value of AR (2) is greater than 0.5, indicating that there is only first-order sequence correlation in the residual series of the equation, and there is no second-order sequence correlation. The model has passed the autocorrelation test.

5.2.3 Missing variables

Therefore, this paper will control the variables related to carbon-emissions as much as possible to reduce the adverse effects of missing variables. Carbon-neutral goal is an important decision made by the state, which needs to be strictly implemented by local governments. Therefore, local governments have an important impact on the level of carbon-emissions. This paper will control individual characteristic variables related to local government officials to solve the problem of missing variables. Table 3 (3) controls the tenure variables of local government officials. The regression results show that the impact of GF on carbon-emissions is still negative, indicating that GF is conducive to the realisation of CN.

Table 3 Robustness Test results based on excluding endogenesis

Variable	*(1)*	*(2)*		*(3)*
	IV-2SLS	*DIFF-GMM*	*SYS-GMM*	*Missing variables*
GF	–340.929***	–125.015**	–117.422**	–339.818***
	(–3.63)	(–2.04)	(–2.03)	(–4.48)
L.C		0.644***	0.855***	
		(129.32)	(61.30)	
Control variable	Y	Y	Y	Y
Fixed time	Y	Y	Y	Y
Individual fixation	Y	Y	Y	Y
N	270	270	300	330
Weak identification test	141.258			
Unidentifiable test	0.0010***			
AR(1)		0.0000***	0.0001***	
AR(2)		0.9059	0.7028	
R^2				0.711

5.2.4 Heterogeneity test

This study initially categorises the 30 provinces into inland and coastal regions based on their coastal proximity. The findings underscore a noteworthy disparity: the influence of GF on carbon emissions exhibits a more pronounced effect within inland areas. Moreover, the examination extends beyond this dichotomy by stratifying the entire sample according to GF development levels, distinguishing between high and low levels of GF implementation. The analysis extends beyond mere statistical outcomes, delving into the potential influence of contextual nuances and policy frameworks on the effectiveness of GF in mitigating carbon emissions. This nuanced examination uncovers a rich tapestry of regional intricacies that contribute to the observed disparities, as detailed in the results presented in Table 4.

Table 4 Regional heterogeneity test results

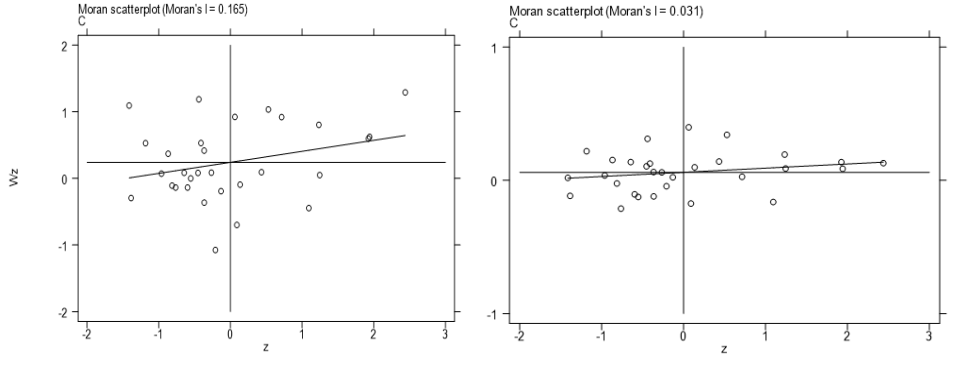
Variable	*(1)*		*(2)*	
	Landlocked	*Coastal*	*Gf < media*	*GF > media*
GF	–571.468***	–137.940	–18.384	–187.097***
	(–6.38)	(–0.70)	(–0.05)	(–2.86)
Control variable	Y	Y	Y	Y
Fixed time	Y	Y	Y	Y
Individual fixation	Y	Y	Y	Y
N	209	121	165	165
R^2	0.730	0.781	0.724	0.795

Intriguingly, the outcomes indicate a heightened impact of GF on carbon emissions within regions characterised by a more advanced level of GF implementation. Delving deeper into these disparities, an in-depth exploration of the differential effectiveness of GF across varied regions unveils multifaceted insights. These variations might be attributed to a myriad of contextual factors, including but not limited to regional policies, infrastructural disparities, economic activities, and divergent environmental concerns. Policies tailored to specific regional needs, varying regulatory frameworks, and differing emphases on sustainable practices could significantly influence the observed disparities.

5.2.5 Spatial spillover test

The utilisation of spatial econometric modelling to explore interregional spillover effects in this research sheds light on intricate regional dynamics. The choice of matrix – proximity and geographic distance matrices – serves as a critical methodological consideration impacting the observed spillover assessments. Upon computing and graphically representing the average carbon emissions for each province in Figure 1, a compelling insight emerges: a distinct clustering tendency within carbon emissions, irrespective of the matrix employed. This clustering hints at regions exhibiting similar emission levels, implying spatial dependencies or linkages among neighbouring areas.

Figure 1 Scatter diagram of carbon-emission



However, the intriguing revelation lies in the comparative analysis between the proximity and geographic distance matrices. The noticeably more pronounced spatial spillover effect identified in the proximity matrix signifies a more robust and immediate interdependency among adjacent regions. This outcome could imply a higher degree of influence or shared characteristics between proximate provinces, potentially attributed to shared economic activities, infrastructural connectivity, or policy interplays fostering concerted environmental impact.

The contrast between the matrices prompts deeper inquiry into the nature of spatial relationships. While both matrices affirm spatial clustering, the amplified spillover effect in the proximity matrix underscores the significance of local interactions or localised effects in driving carbon emissions. This discrepancy could be influenced by factors such as trade networks, resource utilisation patterns, or collaborative initiatives among nearby regions, warranting further investigation into localised policies or collaborative sustainability efforts shaping these observed spatial patterns.

Moreover, the spatial econometric model is used to test. The research results are shown in Table 5. The regression results of column (1) use the proximity matrix, and the regression result of column (2) uses the geographic distance matrix. The regression results show that the impact of GF on carbon-emissions is significant at the level of 1%, which indicates that GF can reduce carbon-emissions. The regression coefficient of W * GF shows that GF in other regions can significantly reduction, indicating that the impact of GF on carbon-emissions has spatial spillover. The negative spatial spillover of carbon-emissions indicates that the local carbon-emission level has reduced. The local government will grasp the competitive advantage of carbon-emissions and reduce carbon-emissions on a large scale to win the approval of the central government. Both LR test and Wald test are significantly positive at 1% level, indicating that the model used in this paper is correct. By regression, we prove hypothesis 2.

Table 5 Test results of spatial correlation

Variable	*(1)*	*(1)*
	Adjacency matrix	*Distance matrix*
GF	–296.723***	–398.299***
	(–4.06)	(–5.04)
W*C	–0.356**	–1.576***
	(–2.25)	(–2.90)
W*GF	–321.783**	–1.4e+03***
	(–2.19)	(–3.07)
Control variable	Y	Y
Fixed time	Y	Y
Individual fixation	Y	Y
N	330	330
LR spatial lag term	41.10***	27.98***
LR spatial error term	41.72***	27.95***
Wald space lag	41.59***	26.55***
Wald space error term	44.70***	28.79***

5.3 Nonlinear test

While the preceding empirical analysis has drawn robust conclusions regarding the impact of GF on carbon emissions, an inherent nonlinearity in this relationship demands further exploration. Consequently, this study employs quantile regression to scrutinise potential nonlinearities in the GF's influence. Table 6 presents regression outcomes for the 1st, 3rd, 6th, and 9th percentiles.

Remarkably, the findings indicate a nuanced pattern: initially, the impact of GF on carbon emissions appears positive yet statistically non-significant. However, as carbon emissions escalate, a shift occurs wherein the influence of GF turns negative and insignificantly impacts emissions, suggesting a lack of substantial effect. Intriguingly, at higher levels of carbon emissions, notably significant at the 1% level, GF emerges as a substantial mitigating factor, significantly reducing emissions. This delineates a nonlinear relationship between GF and carbon emissions – a notable trend where the positive effect of GF becomes more pronounced as carbon emissions reach higher levels.

Table 6 Non-linear test: quantile regression

Variable	*(1)*	*(2)*	*(3)*	*(4)*
	1/10	*3/10*	*6/10*	*9/10*
GF	48.167	–128.961	–248.469	–605.071***
	(0.32)	(–0.66)	(–1.06)	(–3.74)
INV	89.696	50.998	95.247*	128.332*
	(1.37)	(0.88)	(1.77)	(1.80)
FDI	–0.152**	–0.236**	–0.067	–0.157***
	(–2.24)	(–2.29)	(–1.52)	(–3.25)
IND	–2.295	–2.585	–4.938*	–5.279
	(–1.43)	(–1.53)	(–1.85)	(–0.94)
FSUR	5.511***	8.246***	11.474***	13.734***
	(7.66)	(12.00)	(12.66)	(9.49)
UNE	–26.268	–19.182	–0.738	–42.914***
	(–1.29)	(–1.03)	(–0.04)	(–2.63)
TAX	–12.718***	–20.097***	–25.116***	–43.037***
	(–3.56)	(–4.58)	(–5.58)	(–10.94)
URB	–434.521***	–125.658	–247.421*	354.726**
	(–2.87)	(–0.51)	(–1.74)	(2.55)
OPEN	–0.002	–0.015**	–0.023***	–0.038***
	(–0.40)	(–1.97)	(–5.52)	(–7.47)

This multifaceted analysis unveils a nuanced interplay between GF and carbon emissions, revealing a nonlinear relationship contingent upon varying emission levels. Notably, the quantile regression results lend credence to Hypothesis 3, substantiating the hypothesis that the impact of GF on carbon emissions exhibits a nonlinear trajectory. This observation underscores the importance of considering different emission levels, as higher emissions showcase a more conspicuous and significant positive effect of GF in curbing carbon emissions.

However, to comprehensively dissect this nonlinear pattern, conducting subgroup analyses or introducing additional variables, such as regional policies, economic factors, or technological advancements, could offer deeper insights into the driving forces behind these nonlinear dynamics, enriching the study's findings and implications.

5.4 Mediating effect test

The prior analysis in this study primarily focused on examining the direct relationship between GF and carbon emissions, overlooking the intricate mechanisms underlying this impact. To delve deeper into this relationship, this paper endeavours to investigate the mediating effect, illuminating the pivotal role of green innovation as an intermediary mechanism in the transition toward carbon neutrality.

Theoretical underpinnings suggest that green innovation serves as a critical intermediary within the impact of GF on carbon emissions. The regression outcomes in Table 7 offer compelling insights into this interplay. Column (1) highlights the direct impact of GF on carbon emissions within the benchmark regression, while column (2) delineates the impact of GF on green innovation. Notably, the regression results demonstrate that GF notably enhances the level of green innovation, signifying its role in fostering innovative environmental practices.

Table 7 Test of mediating effect (1)

Variable	*(1)*	*(2)*	*(3)*
	C	*GP*	*C*
GF	–333.927***	5.699***	–98.021
	(–4.41)	(18.04)	(–0.89)
GP			–41.391***
			(–2.93)
Control variable	Y	Y	Y
Fixed time	Y	Y	Y
Individual fixation	Y	Y	Y
N	330	330	330
R^2	0.712	0.726	0.719

However, the integration of GF and green innovation in column (3) uncovers a compelling revelation: while the impact of green innovation on carbon emissions is significantly negative, the direct influence of GF on carbon emissions lacks statistical significance. This observation, corroborated by the stepwise regression interpretation method, accentuates the complete intermediary role of green innovation in the impact between GF and carbon emissions. Consequently, this substantiates the premise that GF exerts its influence on carbon emissions primarily through its facilitation of green innovation.

This elucidation through the mediating effect analysis significantly validates Hypothesis 4, affirming the intricate relationship wherein GF's impact on carbon emissions transpires predominantly via the facilitation and enhancement of green innovation initiatives. This insight posits green innovation as a critical mediating force, offering a pathway toward carbon neutrality by catalysing environmentally conscious

innovations. To fortify these findings, empirical evidence or case studies showcasing successful instances of GF-driven green innovation and subsequent carbon emission reductions could be integrated, further enriching the discourse on the transformative power of sustainable innovation in achieving carbon neutrality.

In order to further test whether the industrial structure has an intermediary effect in the process of GF promoting the realisation of carbon-neutral goal, this paper conducts the following intermediary effect test, as well as the regression results are shown in Table 8. Column (1) shows the impact of GF on carbon-emissions, column (2) shows the impact of GF on industrial structure. The regression results show that GF reduces the proportion of the primary industry, and column (3) adds GF and industrial structure to the regression results. The results show that is negative but not significant. According to the interpretation method of regression results of stepwise regression method, the industrial structure does not play a mediating role in the impact, so it cannot prove Hypothesis 5.

Table 8 Test of mediating effect (2)

Variable	*(1)*	*(2)*	*(3)*
	C	*IND*	*C*
GF	–314.348***	–12.454***	–333.927***
	(–4.27)	(–4.06)	(–4.41)
IND			–1.572
			(–1.10)
Control variable	Y	Y	Y
Fixed time	Y	Y	Y
Individual fixation	Y	Y	Y
N	330	330	330
R^2	0.712	0.726	0.719

6 Conclusions and suggestion

By collating the existing literature related to the topic studied in this paper, analysing the current status of research on GF and carbon neutrality, understanding the mechanism of action between GF and carbon neutrality, focusing on how GF affects carbon neutrality, and analysing the research findings of existing literature in the field of GF and carbon neutrality, using the existing research findings as a theoretical basis to propose the research hypothesis of this paper, and then developing the research of this paper.

The recent focus on GF and the carbon-neutral agenda has spurred empirical investigations, revealing that GF indeed holds an inhibitory effect on carbon emissions, thus aiding in the pursuit of achieving carbon neutrality. Acknowledging potential endogeneity concerns between GF and carbon emissions, rigorous measures have been employed to mitigate such issues. Even after meticulously controlling for endogeneity, the study consistently reaffirms the significantly negative impact of GF on carbon emissions. Moreover, the study uncovers regional disparities in the influence of GF on carbon emissions, particularly discernible between coastal and inland areas, as well as regions characterised by varying levels of GF development. Accounting for spatial

spillover effects in carbon emissions, the spatial econometric model validates the presence of GF's impact, exhibiting spatial diffusion across regions.

Furthermore, recognising the potential nonlinear nature of GF's impact, quantile regression analysis unveils a pronounced and significant effect at higher quantiles, indicating a more substantial impact at escalated levels of GF. Delving deeper, the investigation probes into the mediating effect of GF and industrial structure on carbon emissions. Notably, it emphasises the pivotal role of GF in inhibiting carbon emissions by fostering green innovation. Contrarily, industrial structure optimisation does not demonstrate a mediating effect in the process of GF promoting the carbon-neutral goal.

Synthesising these research insights, several strategic recommendations emerge. Firstly, there's a pressing need to bolster the level of GF in China, given its current nascent stage, sluggish development pace, and lack of a mature system. Strengthening the financial sector's focus on GF can leverage its positive impact on carbon emissions, expediting the journey towards achieving carbon neutrality. Secondly, leveraging the observed spatial spillover in the impact of GF on carbon emissions, encouraging local governments to engage in a 'carbon reduction competition' could be instrumental. Capitalising on the competitive dynamics between regions could incentivise local governments to guide enterprises in actively reducing carbon emissions. Lastly, amplifying the focus on enhancing green innovation among enterprises emerges as a critical avenue. The mediating role of green innovation in the GF-carbon emissions nexus suggests that further nurturing innovative practices can yield substantial reductions in carbon emissions. Encouraging innovation through appropriate incentives and active engagement from both enterprises and the public becomes pivotal for this endeavour. In summary, this study advocates for amplifying GF's development, leveraging regional competition for carbon reduction, and nurturing green innovation as pivotal strategies in China's pursuit of achieving the carbon-neutral goal. These actions hold the potential to accelerate progress towards a more sustainable and environmentally conscious future.

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References

Akan T. (2023) 'Renewable energy: moderated, moderating or mediating?', *Applied Energy*, Vol. 347, No. 347, p.121411.

Chen, X. and Chen, Z. (2021) 'Can green finance development reduce carbon emissions? Empirical evidence from 30 Chinese provinces', *Sustainability*, Vol. 13, No. 21, p.12137.

Cowan, E. (1999) 'Topical issues in environmental finance', *Research paper commissioned by the Asia Branch of the Canadian International Development Agency (CIDA)*, Vol. 1, No. 1, pp.1–20.

Ge, X. (2022) 'Study on the effect of agricultural technological progress on agricultural carbon emission effectualness', *Forest Chemicals Review*, No. 2022, pp.78–97.

Guo, J., Zhang, Z. and Meng, L. (2012) 'China's provincial CO_2 emissions embodied in international and interprovincial trade', *Energy Policy*, Vol. 42, No. 42, pp.486–497.

Guo, W., Yang, B., Ji, J. and Liu, X. (2023) 'Green finance development drives renewable energy development: Mechanism analysis and empirical research', *Renewable Energy*, Vol. 215, No. 215, p.118982.

Labatt, S. and White, R.R. (2002) *Environmental Finance: a Guide to Environmental Risk Assessment and Financial Products,* John Wiley & Sons.

Lan, J., Wei, Y., Guo, J., Li, Z. and Liu, Z. (2023) 'The effect of green finance on industrial pollution emissions: evidence from China', *Resources Policy*, Vol. 80, No. 80, p.103156.

Li, C., Chen, Z., Wu, Y., Zuo, X., Jan, H., Xu, Y., Zeng, B., Zhao, G. and Wan, Y. (2022a) 'Impact of green finance on China's high-quality economic development, environmental pollution, and energy consumption', *Frontiers in Environmental Science*, Vol. 10, No. 10, p.1032586.

Li, J., Dong, K., Taghizadeh-Hesary, F. and Wang, K. (2022b) '3G in China: how green economic growth and green finance promote green energy?', *Renewable Energy*, Vol. 200, No. 200, pp.1327–1337.

Long, Z., Zhang, Z., Liang, S., Chen, X., Ding, B., Wang, B., Chen, Y., Sun, Y., Li, S. and Yang, T. (2021) 'Spatially explicit carbon emissions at the county scale', *Resources, Conservation and Recycling*, Vol. 173, No. 173, p.105706.

Lv, C., Bian, B., Lee, CC. and He, Z. (2021) 'Regional gap and the trend of green finance development in China', *Energy Economics*, Vol. 102, No. 102, p.105476.

Pu, Z., Yue, S. and Gao, P. (2020) 'The driving factors of China's embodied carbon emissions: a study from the perspectives of inter-provincial trade and international trade', *Technological Forecasting and Social Change*, Vol. 153, No. 153, p.119930.

Qin, M., Su, C.W., Zhong, Y., Song, Y. and Lobont, O. (2022) 'Sustainable finance and renewable energy: promoters of carbon neutrality in the United States', *Journal of environmental management*, Vol. 324, No. 324, p.116390.

Salazar, J. (1998) 'Environmental finance: linking two worlds', Presented at a *Workshop on Financial Innovations for Biodiversity*, Bratislava, Slovakia, pp.2–18.

Shubik, M. (1975) 'On the eight basic units of a dynamic economy controlled by financial institutions', *Review of Income and Wealth*, Vol. 21, No. 2, pp.183–201.

Sun, L., Wang, Q., Zhou, P. and Cheng, F. (2016) 'Effects of carbon emission transfer on economic spillover and carbon emission reduction in China', *Journal of Cleaner Production*, Vol. 112, No. 112, pp.1432–1442.

Wang, G., Li, S. and Yang, L. (2022) 'Research on the pathway of green financial system to implement the realization of China's carbon neutrality target', *International Journal of Environmental Research and Public Health*, Vol. 19, No. 4, p.2451.

Wang, X., Wu, J., Wang, Z., Jia, X. and Bai, B. (2020) 'Accounting and characteristics analysis of CO2 emissions in Chinese Cities', *Chinese Journal of Urban and Environmental Studies*, Vol. 8, No. 1, p.2050004.

Wang, Z., Li, Y., Cai, H. and Wang, B. (2018) 'Comparative analysis of regional carbon emissions accounting methods in China: production-based versus consumption-based principles', *Journal of Cleaner Production*, Vol. 194, No. 194, pp.12–22.

Yang, Y., Su, X. and Yao, S. (2021) 'Nexus between green finance, fintech, and high-quality economic development: empirical evidence from China', *Resources Policy*, Vol. l74, No. 174, p.102445.

Zhang, Z., Fu, H., Xie, S., Faura, J.C. and Urinov, B. (2023) 'Role of green finance and regional environmental efficiency in China', *Renewable Energy*, Vol. 214, No. 214, pp.407–415.

Zhou, X., Tang, X. and Zhang, R. (2020) 'Impact of green finance on economic development and environmental quality: a study based on provincial panel data from China', *Environmental Science and Pollution Research*, Vol. 27, pp.19915–19932.

Zhu, X. (2022) 'Does green credit promote industrial upgrading? Analysis of mediating effects based on technological innovation', *Environmental Science and Pollution Research*, Vol. 29, No. 27, pp.41577–41589.

Zhu, X. and Yang, Y. (2023) 'The pollution reduction effect of official turnover: evidence from China', *Science of The Total Environment*, Vol. 868, No. 868, p.161459.