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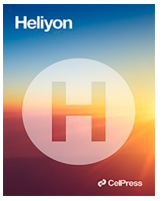

The impact of green finance on carbon emission efficiency

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ABSTRACT

Green finance plays a pivotal role in guiding and incentivizing private capital to invest in low-carbon industries and initiatives. This study utilizes data of Chinese cities from 2006 to 2022 to investigate the influence of green finance on carbon emission efficiency. The results show that green finance significantly contributes to enhancing carbon emission efficiency. The impact of green finance on carbon emission efficiency is subject to a dual threshold effect, which depends on the level of regional economic development. Regional innovation emerges as a vital channel through which green finance influences carbon emission efficacy. Moreover, the sensitivity of carbon emission efficiency to the green finance index shows an inverted U-shaped trend. Green support is most significant in green finance sub-dimensions. These findings provide valuable theoretical support for the role of green finance in fostering carbon efficiency improvement and provide essential insights for formulating effective policy strategies.

1. Introduction

In response to the escalating challenge of global climate change, countries around the world have set ambitious goals aimed at mitigating greenhouse gas emissions and preserving the ecological environment. China, as the world's largest carbon emitter, has also committed to achieving carbon peak by the year 2030 [1]. To achieve the goal of carbon neutrality by the year 2060, it is imperative to expedite economic restructuring, transformation, and upgrade to promote low-carbon development. In this endeavor, green finance plays a pivotal role. Green finance encompasses economic activities aimed at supporting environmental enhancement, addressing climate change, and promoting the efficient utilization of resources. It involves the provision of financial services for project investment, financing, project operation, and risk management in sectors such as environmental protection, energy conservation, clean energy, green transportation, and green buildings [2].

Green finance leverages financial instruments and policies, including green credit, green bonds, green insurance, and carbon finance, to steer the flow of capital towards low-carbon industries and projects. It serves as a powerful incentive to enhance energy efficiency and reduce pollution emissions. Furthermore, green finance aids society in effectively addressing the risks and challenges posed by climate change and plays a crucial role in facilitating the transition toward a more sustainable and environmentally responsible economic model [3]. "Carbon emission efficiency" represents a pivotal concept within the realm of green finance. It pertains to the quantity of carbon dioxide (CO_2) emissions and serves as a crucial metric for evaluating the carbon emissions during the production processes [4]. The progression toward a low-carbon economy involves diminishing the intensity of carbon dioxide

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emissions without exerting detrimental effects on economic growth or the standard of living and holds immense significance in achieving sustainable development objectives.

Financial institutions should embrace environmental and social responsibilities [5]. With China's environmental protection system continually improving, the advancement of green finance stands as a pivotal direction for China's financial industry in the future. Does the current allocation of financial resources have an impact on the environment and the quality of economic growth in China? Can green finance foster the relationship between economic development and environmental quality, ultimately achieving mutually beneficial outcome for both the economy and the environment? What mechanisms and approaches can green finance effectively curtail carbon emissions? Research on green finance focuses on green and low-carbon development, while lacks substantial empirical evidence. Thus, it is imperative to undertake a comprehensive study to delve into the intricacies of green finance development.

This paper empirically studies the main channels and mechanisms of green finance on carbon emission reduction. By elucidating the internal logic underpinning the carbon emission reduction effect of green credit, it endeavors to provide more empirical evidence for the role of green finance in reducing pollution, mitigating carbon emissions, and facilitating the transition to a greener economy. These findings can offer valuable policy insights that promote the advancement of green credit.

This paper is structured in six sections, section 1 is introductory. Section 2 reviews relevant literature. Section 3 provides the theoretical analysis. Section 4 describes the models and variables. The empirical results are displayed in Section 5. Finally, main conclusions are drawn, and policy implications are pointed out in the sixth section.

2. Literature review

2.1. Carbon emission efficiency

Studies have sought to understand how green finance affects carbon emission efficiency, particularly in terms of reducing emissions intensity per unit of economic output. Sharif, Saqib et al. [6] investigated the direct impact of green finance on carbon emission efficiency in 285 Chinese cities and found that the combined influence of digital finance and green technology innovation significantly contributes to local carbon emission efficiency. Digital finance has the potential to reduce national carbon emissions and enhance carbon efficiency, and plays a role in promoting the development of green technologies and the upgrading of China's industrial structure [6]. Xiong and Sun [7] examined the relationship between green financing development and carbon emissions in Chinese provinces through a fuzzy-set qualitative comparative analysis approach. Meo and Abd Karim [8] explored the connection between green finance and carbon dioxide emissions and found that green finance emerged as the most effective financial instrument for mitigating emissions, offering a cost-effective means of reducing carbon outputs. Zhou et al. [9] tested the impact of green finance on economic development and environmental quality in 30 Chinese provinces from 2010 to 2017 and found that green finance has a positive impact on economic development and improving environmental quality, while varies at different levels of economic development. Sheraz et al. [10] explored the moderating effects of globalization on financial development, energy consumption, human capital, and carbon emissions in G20 countries from 1986 to 2018. The study found that financial development and human capital reduced carbon emissions, but gross domestic product (GDP) and energy consumption increased carbon emissions. Zhao et al. [11] explored the green economic efficiency of 30 Chinese provinces using the super slacks-based measurement (Super-SBM) model with undesirable outputs and found that the green economic efficiency of different regions varied significantly and showed a gradient in the eastern, central and western regions. Li et al. [12] analyzed the impact of carbon finance on carbon emissions in the Beijing-Tianjin-Hebei region using the log-mean deviation index model and found that green credit reduced carbon emissions, while carbon trading increased carbon emissions.

2.2. Green finance on industries

Researchers have examined the impact of green finance on different sectors and industries, assessing how it can incentivize environmentally responsible practices and lower carbon emissions across various economic sectors. Guo et al. [13] examined the long-term equilibrium relationship between green finance, fertilizer use, and agricultural carbon emissions in China and revealed the positive correlation between fertilizer use and agricultural carbon emissions. However, green finance can effectively reduce agricultural carbon emissions. It is expected to make a substantial contribution to both the reduction of fertilizer use and agricultural carbon emissions. Ren et al. [14] explored the relationship between the level of green financial development, non-fossil energy consumption, and carbon intensity and uncovered that the rapid growth of China's green finance industry led to a reduction in carbon intensity. Gholipour, Arjomandi, and Yam [15] analyzed green real estate financing and the construction sector and found the positive effect of green real estate financing on reducing CO_2 emissions within the construction sector. This underscores the potential role of green finance in mitigating emissions in the real estate and construction domain.

2.3. Green finance on renewable energy

Investigations have been conducted to determine how green finance supports the development and adoption of renewable energy sources, thereby contributing to reduced carbon emissions associated with conventional energy production. Ikram [16] found that green growth, technological innovation, and the stringency of environmental policies had negative impacts on long-term carbon dioxide emissions. Sadiq, Amayri, Paramaiah et al. [17] explored the long-term linkages between various variables in South Asia and highlighted the critical roles of green bonds, greenhouse gas emission reductions, green economic development, and R&D expenditures

in green financial development and renewable energy production. Mngumi, Shaorong, Shair et al. [18] investigated the role of green finance in reducing CO_2 emissions in BRICS countries and found that an increase in the use of renewable energy sources and advancements in the green finance development index contributed to reduced CO_2 emissions. Murshed, Mahmood, Ahmad et al. [19] examined the pathway for Argentina to achieve carbon neutrality by 2050. Their research showed that increasing the share of renewable energy output in the country's total output reduces sectoral CO_2 emissions. Sun, Fang, Iqbal et al. [20] investigated the effect of financial stability on climate risk and found the importance of mitigating climate change for long-term financial sustainability. Zhou et al. [9] examined the impact of green finance on economic development and environmental quality. The results demonstrated that green finance promotes economic development and improves environmental quality. Ren et al. [20] explored the relationship between green finance, non-fossil energy utilization, and carbon intensity in China and found that the development of green finance promoted the reduction of carbon intensity. Qin et al. [22] revisited the role of financial development and renewable electricity on carbon emissions in China and found that improvements in financial development, renewable electricity generation, and human capital were associated with reduced carbon emissions.

2.4. Green finance on innovation

Studies have assessed how green finance encourages innovation in sustainable technologies and practices, leading to improvements in carbon emission efficiency. Irfan, Razzaq, Sharif et al. [23] uncovered the substantial role of green finance in promoting green innovation and identified industrial structure, economic growth, and R&D investment as the core transmission channels. Zhou et al. [24] investigated the impact of fintech and green finance on green economic growth in China and indicated that both fintech and green finance significantly promote green economic growth. Fintech innovation drove green economic growth mainly through green credit and green investment. Sharif, Saqib, Dong et al. [6] examined the impacts of green technological innovations and green financing on CO_2 emissions in G7 countries and revealed that green technology innovation and green financing exerted a significant negative effect on CO_2 emissions.

2.5. Green finance on credit markets

Researchers have examined the role of green finance in shaping credit markets, including the availability of green loans and investments, which can drive environmentally friendly projects. Meo [8] explored the relationship between carbon dioxide emissions, energy efficiency, green energy index, and green finance in the top 10 economies that support green finance and found that green bonds served as an effective means to promote green energy projects and reduce CO_2 emissions. Under stringent carbon emission policies, manufacturers can achieve a win-win situation with their suppliers through green investment, enhancing social welfare and profits [25]. Ren [21] examined the interrelationship between carbon futures and green bond markets and found that carbon futures prices had a positive impact on the green bond index in the medium to long term while exhibited erratic behavior in the short term. Al Mamun [26] investigated the impact of green finance on decarbonization and found that green finance significantly reduced carbon emissions in both the short and long term. Green bonds had a more pronounced impact in developed credit markets and economies with higher innovation success and greater climate change risk. Jin et al. [27] assessed the factors influencing the efficiency of green finance in corporate financing in China's energy-saving and environmental protection industry and revealed that banks remained the primary credit providers. Umar [28] assessed the impact of carbon-neutral lending on credit risk in the Eurozone and discovered a negative correlation between carbon-neutral lending risk and default risk across lending institutions of different sizes. Wang [29] conducted an analysis of 815 green finance and energy policy publications and highlighted key journals, scholars, research findings, and future research priorities in the field. Jin et al. [27] assessed the financing efficiency of energy conservation and environmental protection listed companies in China and found that banks played a dominant role in the financial market, while firms listed on the Second Board exhibited higher financing efficiency.

2.6. Green finance on different economies

The impact of green finance on different economies, ranging from developed to emerging markets, has been a subject of investigation to understand how it influences carbon emissions on a global scale. Mohsin [30] investigated the impact of environmental technology innovations, economic complexity, renewable energy generation, and environmental taxes on CO_2 emissions in G10 countries and found that greater adoption of environmentally friendly technologies, economic complexity, and renewable energy generation had a positive impact on reducing carbon emissions. Notably, Nepal and Iceland achieved the highest scores, while Singapore and Israel scored the lowest. Umar [28] analyzed the impact of carbon-neutral loans on credit risk in the Eurozone and demonstrated a negative correlation between exposure to carbon-neutral loans and default risk. Chuc [31] examined the integration of energy security, economy, and the environment in Belt and Road Initiative member countries and highlighted substantial variations in energy financing patterns, renewable energy consumption, and carbon emission trends. Saqib [32] studied the relationship between green energy, non-renewable energy, financial development, economic growth, and carbon footprint across 63 emerging and developed economies and found that non-renewable energy consumption contributes to increased carbon footprints, while green energy adoption mitigates environmental degradation. Sadiq [17] explored the impact of green technology innovation on carbon emission efficiency and analyze the mediating effects of economic development, urbanization, and financial development in 32 developed countries that have proposed carbon-neutral targets as a research sample and highlighted the mediating roles of economic development and urbanization in shaping the relationship between green technological innovation and carbon emission efficiency. Saqib [33]

investigated the role of green technology innovation and green financing in reducing CO_2 emissions in G7 countries and revealed that both green technology innovation and green financing had a negative impact on CO_2 emissions.

2.7. Financial inclusion and carbon emissions

Le [34] explored the impact of financial inclusion on carbon dioxide emissions in 31 Asian countries and found that financial inclusion contributed to an increase in carbon dioxide emissions. Ji [35] investigated the impact of carbon neutrality on the investment performance of equity mutual funds in BRICS countries and indicated that green funds outperformed black and brown funds, with China's green funds showing particularly strong performance.

Green finance has the potential to enhance high-quality economic development by optimizing resource allocation, improving industrial structure, and fostering technological innovation. However, there lacks empirical studies on the impact of green finance on carbon emission efficiency and the ranking of factors affecting carbon emission efficiency or studies that delve into the sensitivity of carbon emission efficiency to green finance. This paper ranks the relative importance of factors influencing carbon emission efficiency. Furthermore, we utilize the random forest model to analyze the sensitivity of carbon emission efficiency to green finance.

3. Theoretical hypotheses

3.1. The impact of green finance on carbon emission efficiency

Green financing offers financial support to enterprises for implementing environmental projects [27]. It enables enterprises to upgrade their production machinery and technology, resulting in reduced carbon emissions. Green financial institutions also provide technical assistance and managerial expertise, facilitating the execution of environmental protection initiatives. Green finance can incentivize enterprises to increase their investments in environmental conservation [7]. By issuing environmental protection bonds, establishing green funds, and attracting more capital to this sector, green finance can enhance the return on investment for environmental initiatives. Consequently, enterprises are encouraged to enhance their environmental protection investments, thereby improving their efficiency in reducing carbon emissions and reducing associated costs.

Green financing can facilitate business transformation and upgrades by mitigating environmental risks. Businesses can reduce their carbon footprint by adopting greener manufacturing practices and technology. Green financial institutions can assist enterprises in managing environmental risks and complying with increasingly stringent environmental regulations through risk management and environmental assessments. As global awareness of environmental conservation grows, enterprises can leverage green finance to align with environmental requirements and avoid pollution-related issues. In addition, green finance provides enterprises with a stable and trustworthy source of funding [27], which enables enterprises to sustain investments in environmentally responsible practices and encourages further investment in environmental protection, ultimately enhancing the efficiency of carbon emission reduction efforts [8]. Thus, we propose the following hypothesis.

Hypothesis 1. Green finance can significantly enhance carbon emission efficiency.

3.2. Regional heterogeneity differences

The impact of green finance on carbon emissions reduction is likely to vary by region, reflecting differences in economic development [11,19]. In China, the eastern coastal areas are particularly susceptible to the influence of green financing. In pursuit of green and low-carbon development goals, local governments in these areas have been actively supporting the growth of the green finance industry, creating a conducive policy environment. Consequently, green financing is poised to have a more pronounced effect on carbon emission efficiency in these regions by facilitating the upgrading and optimization of industrial structures and fostering the development of a low-carbon economy.

The central area is characterized by a dominance of heavy industry and traditional manufacturing, coupled with a lower level of economic development. It may exhibit higher carbon emission intensity but a less developed green financing market. Consequently, the impact of green funding on the region's ability to reduce carbon emissions may be less substantial. The western area faces challenges related to its challenging topography, inefficient transportation networks, and aging infrastructure, which have contributed to a slower pace of economic development. The policy and commercial environment for green financing in the western region lags behind, limiting the potential impact of green finance on reducing carbon emissions efficiency. Therefore, Hypothesis 2 is put forward.

Hypothesis 2. The effect of green finance on carbon emission efficiency is most significant in the eastern region of China, followed by the central region, and the least in the western region.

3.3. The role of regional innovation capacity

Green finance plays a pivotal role in enhancing the innovation capabilities of enterprises. The growth and evolution of the green financial market necessitate continuous innovation in financial products and services [36]. Financial institutions must engage in ongoing research and development (R&D) to create novel green financial offerings such as green bonds and carbon emissions trading. These innovations span areas like environmental protection technology and carbon emissions assessment, demanding high levels of technological and innovative expertise from financial institutions [37].The advancement of green finance requires enterprises to

continually innovate and undergo transformations and upgrades. To execute environmental projects and technological enhancements, enterprises must possess technical and innovative capabilities to enhance production processes, equipment, and reduce carbon emissions [38,39]. The development of green finance can stimulate research and innovation in environmental protection technology. As the green financial market expands, financial institutions will explore and innovate more environmentally friendly financial products and services, thereby promoting research and innovation in environmental technology. To meet the demands of the green financial market, enterprises will persist in researching and developing new environmental protection technologies and products, consequently improving carbon emission efficiency [40].

Innovation plays a pivotal role in advancing carbon emission efficiency. Innovation propels the continuous growth and enhancement of the green financial market, providing diverse and flexible financing avenues for the environmental protection industry [41–43].Green finance integrates environmental protection and resource utilization efficiency into financial activities, delivering financing and investment services to the environmental protection sector. These financial instruments' constant innovation offers environmental protection industries flexible and diversified financing methods, ultimately fostering investment in environmental protection and enhancing carbon emission efficiency. Innovation can also standardize the green financial market, improving transparency, stability, and reliability of financing channels, further supporting the environmental protection industry. Innovation drives continuous upgrades and improvements in environmental protection technology and services, reducing environmental costs and carbon intensity [44,45].As technology advances and innovates, environmental protection technologies and services continually improve, lowering environmental costs and carbon intensity. These innovations provide more efficient and economical environmental solutions and accelerate the application and dissemination of environmental technologies and services, broadening access to environmental solutions.

In addition, innovation enhances the competitiveness and social standing of environmental protection enterprises, driving improvements in carbon emission efficiency. With the growing awareness of environmental concerns and social expectations for environmental responsibility, enterprises recognize the significance of environmental protection and the market competition among environmental protection enterprises intensifies. To remain competitive, these enterprises must consistently introduce environmentally friendly and efficient products and services, improving their market positioning and social image [14]. Hypothesis 3 is constructed.

Hypothesis 3. Green finance can enhance regional innovation capabilities, consequently contributing to improved carbon emission efficiency.

3.4. The characteristics of different GDP development stages

With the expansion of the economy, environmental issues, especially climate change, are becoming increasingly prominent. Green finance enhances carbon emissions efficiency while promoting the growth of environmental protection enterprises and technologies. Green finance plays an increasingly vital role as the economy develops. Economic growth leads to stronger policy support for green financing [46].Governments aim for a virtuous cycle of economic development and environmental protection, emphasizing sustainability and urging enterprises to enhance environmental protection and energy-saving measures. Stricter environmental standards and regulations require increased resource allocation. Governments also offer incentives such as tax breaks and financial subsidies to encourage green initiatives, facilitating the growth of green financing [44].

Progress in green financing encourages technical advancements and the adoption of environmental protection technologies, enhancing carbon emission reduction efforts. Businesses receive financial support for R&D, and application of environmental protection technologies, further improving carbon emission efficiency. Economic growth accelerates technical innovation [36,47]. Increased investment in environmental protection technologies, accelerated by the growth of green finance, leads to higher carbon emission efficiency and competitiveness. Enterprises can implement eco-friendly practices at a reduced cost with the support of green finance. In an increasingly interconnected world with heightened environmental awareness, green finance becomes a leading global financial movement. Governments and financial institutions worldwide prioritize environmental conservation and sustainable development [44]. Green finance replaces traditional forms of international financing, providing greater support for global carbon emissions reduction efforts. Therefore, Hypothesis 4 is proposed.

Hypothesis 4. The positive impact of green finance on carbon emission efficiency exhibits an increasing marginal effect.

3.5. The sensitivity of carbon efficiency to green finance

The growth of the green finance sector has increased carbon emission reductions by raising business understanding of environmental issues and the necessity of sustainable development [19,20]. To boost their green credentials and competitiveness, enterprises are increasing their spending on renewable energy and environmentally friendly technologies thanks to the green finance market [48,49]. The fast growth of the green finance sector has led to rising green finance regulations and a growing awareness of carbon emissions among enterprises. As the green finance sector has expanded rapidly, governments, financial institutions, and enterprises have adopted a number of regulations and guidelines to promote and regulate this kind of financing [50].Green finance alternatives for enterprises have expanded due to the emergence of a wide range of goods and services in this sector. These efforts have encouraged the reduction of carbon emissions and increased business investment and investigation in environmental preservation [51,52].

As the green finance market has developed, enterprises' understanding of green finance standards and environmental protection has grown, while the level of control over carbon emissions has plateaued [53]. Businesses' ability to increase their carbon emission

efficiency has been limited, and their responsiveness to green finance has diminished. Meanwhile, as green finance matures, green financial standards converge, enterprises gain expertise in practice, green finance's regulatory function weakens, and enterprises increasingly rely less on environmental consciousness and sustainability. Green finance has been standardized throughout time, which has led to an increase in environmental protection measures and a better knowledge of green finance on the part of enterprises [54,55]. As enterprises learn to protect their own environment, they become less reliant on the green finance market for guidance and assistance, and their own operational management capabilities become the limiting factor in the rate at which they can reduce carbon emissions. us, we put forward Hypothesis 5.

Hypothesis 5. With the development of green finance, the sensitivity of carbon emission efficiency of enterprises to green finance will first increase and then decrease.

4. Models and variables

4.1. Models

We use the panel two-way fixed effect model to examine the potential direct impact of green finance on carbon emission efficiency. The panel two-way fixed effects model is a robust method for analyzing panel data, which helps mitigate issues related to omitted variables and exogeneity bias. The equation is shown in equation (1).

$$CO_2Eff_{it} = b_1 + b_2 GFinaDEX_{it} + b_3 control_{it} + \mu_i + \lambda_i + \varepsilon_{it} \tag{1}$$

i and t denote the city and the year, respectively. CO_2Eff_{it} represents the carbon efficiency index of city i in year t, and the green finance index of city i in year t. μ_i and λ_t are city and year effects, respectively. ε_{it} is the random disturbance term.

Impact of green finance on carbon efficiency may vary across different stages of economic development. Thus, we construct a threshold model, as illustrated in Equation (2).

$$CO_2Eff_{it} = g_1 + g_2\, GFinaDEX_{it} \times I(\, GDP_{it} < c_1) + g_2\, GFinaDEX_{it} \times I(c_1 < GDP_{it} < c_2) + g_3\, GFinaDEX_{it} \times I(\, GDP_{it} > c_2) + g_4\, control_{it} + e_{it} \tag{2}$$

GDP_{it} is the total regional GDP of city i in year t, which is also the threshold variable. I (·) is the indicator function, and is the threshold value of the threshold variable. Green finance may have an impact on regional innovation capacity. As shown in equations (3)–(5), a panel mediating effect model is constructed to test the mechanism. $PatCnt_{it}$ is the mediating variable, indicating the number of patents granted in city i in year t.

$$CO_2Eff_{it} = b_1 + b_2 GFinaDEX_{it} + b_3 control_{it} + m_i + l_t + e_{it} \tag{3}$$

$$PatCnt_{it} = \beta_1 + \beta_2 GFinaDEX_{it} + \beta_3 control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{4}$$

$$CO_2Eff_{it} = \beta_1 + \beta_2 GFinaDEX_{it} + \beta_3 PatCnt_{it} + \beta_4 control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{5}$$

4.2. Variables

The variable being explained is CO_2Eff_{it} (carbon emission index). Capital, labor and energy are chosen as input indicators. GDP is selected as desirable output, and carbon emission is selected as the undesirable output. The super-efficiency SBM model with undesirable output is applied to calculate carbon emission efficiency. Capital is measured by fixed asset investment. Labor is measured by the total number of employees in the three industries. Energy input is measured by total energy consumption. The indicators are shown in Table 1. The sample time range is 2006–2022.

The traditional data envelopment analysis (DEA) model relies on radial distance functions from either the input or output perspective to calculate efficiency scores. In practical applications, the radial criterion is often not met. Tone introduced the non-radial DEA-SBM model to quantify the improvement potential or "slack". [56]This model overcomes the drawbacks of traditional DEA models. The super-SBM model permits efficiency values greater than or equal to 1. In essence, the super-SBM model offers a more robust and flexible approach to evaluate the efficiency of decision-making units (DMUs), particularly when traditional radial DEA models may not provide accurate assessments.

Table 1
Input-output indicators.

Indicators	Variables	Meanings
Input indicators	Capital	Fixed asset investment (billion yuan)
	Labor	Total number of employees in the tertiary sector (million people)
	Energy	Total energy consumption (million tons of standard coal)
Desirable indicator	GDP	GDP (billion yuan)
Undesirable indicator	Carbon emission	Carbon dioxide emissions (tons)

The super-SBM models are shown as follows. x_{ij} denotes the jth input variable for the ith DMU and y denotes the kth output variable, where $i = 1,2,\ldots,n.j = 1,2,\ldots,m.k = 1,2,\ldots,s$. U_j and V_k denote the strong effective target value of the jth input variable and the first output variable. λ_j and γ_k represent the relaxation weight of the jth input variable and the kth output variable.

$$w_{ij} = \frac{\lambda_j U_j}{\sqrt{\sum_{i=1}^{n}\left(\frac{x_{ij}}{U_j}\right)^2}} \tag{6}$$

$$w_{ik} = \frac{\gamma_k V_k}{\sqrt{\sum_{i=1}^{n}\left(\frac{y_{ik}}{V_k}\right)^2}} \tag{7}$$

Where, w_{ij} in equation (6) and w_{ik} in equation (7) represent the target weights for the jth input variable and the kth output variable of the i-th decision unit, respectively.

For each DMU, the output vector of the SBM model is calculated by Equation (8). Its efficiency value is calculated by Equation (9). DMUs can be evaluated and ranked according to their relative efficiency values.

$$z_i = \sum_{j=1}^{m} w_{ij}x_{ij} + \sum_{k=1}^{s} w_{ik}y_{ik} \tag{8}$$

$$E_i = \frac{\sum_{k=1}^{s} w_{ik}y_{ik}}{z_i} \tag{9}$$

The explanatory variable is green finance index ($GFinaDEX_{it}$). Evaluation of the green finance index needs to establish a comprehensive indicator evaluation system. Studies have mostly characterized the level of green financial development by green credit, while it is difficult to comprehensively reflect the connotation of green finance. This paper constructs a green financial evaluation system from seven perspectives including green credit, green investment, green insurance, green bonds, green support, green funds and green rights and interests, and calculates the green financial evaluation index of each city using the entropy value method. The sample time range is from 2006 to 2022. The variables at all levels are shown in Table 2.

The intermediate variable is number of patents granted ($PatCnt_{it}$), which is the sum total of patents awarded to a single person or group within a time frame (usually one year). As a reflection of an entity's competence and contribution to the creation of new technologies in a specific sector, the number of patents awarded is frequently regarded as one of the most important indications of innovation capacity. This paper uses patents as a proxy for innovation because of their potential as a neutral party in the process of green funding for carbon efficiency.

The threshold variable is regional GDP (GDP_{it}), which is the final result of production activities of all resident units in a country (or region) over a period of time. GDP is the core indicator of national economic accounting and an important indicator of the economic status and development level of a country. Since green finance may have different effects on carbon emission efficiency at different stages of GDP development, GDP is used as the threshold variable.

The following variables are selected as control variables. Urbanization level ($UrbRate_{it}$) is measured by urbanization rate. Industrial structure ($IndRate_{it}$) is measured by the share of secondary industry. Openness ($TradeRate_{it}$) is measured by the share of imports and exports in GDP. Innovation level ($RnDRate_{it}$) is measured by the share of R&D expenditures in GDP. Energy utilization ($EnergyEffi_{it}$) is measured by energy consumption per unit of GDP.

The data are obtained from the China Statistical Yearbook, the statistical yearbooks of each province, statistical bulletins and the Guotaian database [57,58]. The time range is 2006–2022, and the sample range is most prefecture-level cities in China. The missing

Table 2
Green finance index evaluation system.

Level 1 Indicators	Level 2 Indicators	Proxy variables	Properties
Green credit	Share of credit for environmental projects	Total credit for environmental projects in the city/total credit for the city	+
Green investment	Investment in environmental pollution control as a percentage of GDP	Environmental pollution control investment/GDP	+
Green insurance	Extent of promotion of environmental pollution liability insurance	Environmental pollution liability insurance income/total premium income	+
Green bonds	Degree of Green Bond Development	Total Green Bonds Issued/Total All Bonds Issued	+
Green support	Percentage of financial environmental protection expenditure	Income gap between urban and rural residents	+
Green fund	Percentage of Green Fund	Total market value of green funds/Total market value of all funds	+
Green Rights	Green equity development depth	Carbon trading, energy use rights trading, emission rights trading or total equity market trading	+

values are filled by neural network interpolation. Descriptive statistics of the variables are shown in Table 3.

5. Empirical results

5.1. Benchmark regression

This paper investigates the impact of green finance on carbon emission efficiency using the Green Finance Index and uses the time fixed effect model. The benchmark regression results are shown in Table 4 and Table 5. The coefficients of the core explanatory variables in the eight regression equations are positive and pass the significance test at a significance level of 0.01, indicating that green finance and its various aspects have a strong explanatory and promotional effect on carbon emission efficiency. These findings are in line with prior research [1–3].

Green finance plays a vital role by providing financial support and capital security to environmental enterprises, reducing their financing costs, and enabling them to invest more in environmental projects and technological R&D. Consequently, this investment leads to improved carbon emission efficiency. Green credit offers low-interest loans to green industries, reducing their costs and expediting their development, which facilitates technology and equipment upgrades, enhances productivity, and ultimately reduces carbon emissions [6].

Green investment involves funding environmental protection and low-carbon industries, offering crucial financial support to the environmental protection sector. This support accelerates the growth of green industries, allowing them to introduce new technologies and equipment, improve production efficiency, reduce energy consumption, and consequently enhance carbon emission efficiency.

Green insurance provides protection to green industries against potential losses in the production process, instilling greater confidence in enterprises to invest in environmental protection projects. The presence of insurance safeguards the safety and assets of enterprises, encouraging more proactive investment in environmental protection and, consequently, a reduction in carbon emissions.

In summary, the findings confirm that green finance, along with its components, significantly contributes to improving carbon emission efficiency by providing financial support, reducing costs, and fostering a conducive environment for environmental protection and sustainability.

The introduction of green bonds plays a pivotal role in enhancing carbon emission efficiency by offering investors a channel to allocate funds to environmental projects. This influx of financial support empowers environmental protection firms, facilitating technological and equipment upgrades and enhancing production efficiency, ultimately leading to a reduction in carbon emissions.

Green funds provide additional financial backing to environmental protection industries. It enables enterprises to adopt new technologies and equipment, thus improving production efficiency and reducing energy consumption, thereby promoting overall carbon emission efficiency.

Green equity, involving investments in shares of listed companies within the environmental protection industry, provides companies with increased financial resources and investor attention. It encourages companies to become more proactive in environmental protection investments, leading to productivity improvements and reduced carbon emissions.

The category of green support encompasses various environmental protection industry support programs, such as government-issued environmental protection industry support policies and initiatives from environmental protection industry associations. These programs offer valuable support and services to the environmental protection industry, thereby facilitating smoother operations and contributing to the enhancement of carbon emission efficiency.

5.2. Robustness test

To ensure the robustness of the main regression results, this paper employs these four robustness test methods, which are essential

Table 3
Descriptive statistics of the variables.

Variables	Observations	Maximum	Minimum	Mean	Standard deviation
CO_2Eff	3043	2.079	0.047	0.460	0.198
GFinaDEX	3043	0.746	0.057	0.318	0.098
GDPPC	3043	90,497	55	2819	4539
PatCnt	3043	19.017	0.000	17.261	1.902
TradeRate	3043	8.134	0.000	0.239	0.467
IndRate	3043	0.819	0.032	0.493	0.493
EnergyEffi	3043	0.080	0.002	0.019	0.011
UrbRate	3043	2.362	0.002	0.501	0.226
RnDRate	3043	1.259	0.000	0.023	0.046
Green credit	3043	0.134	0.007	0.048	0.018
Green investment	3043	0.034	0.000	0.012	0.005
Green insurance	3043	0.056	0.002	0.021	0.008
Green bond	3043	0.026	0.000	0.007	0.003
Green support	3043	0.031	0.000	0.007	0.004
Green fund	3043	0.134	0.000	0.048	0.018
Green equity	3043	0.098	0.001	0.024	0.011

Table 4
Benchmark regression results 1.

	CO_2Eff	CO_2Eff	CO_2Eff	CO_2Eff
	(1)	(2)	(3)	(4)
GFinaDEX	0.3308***			
	(11.90)			
Green credit		1.3837***		
		(11.23)		
Green investment			4.3922***	
			(10.187)	
Green insurance				2.9407***
				(10.3)
IndRate	0.0617**	0.0479**	0.0425*	0.0465*
	(2.27)	(1.88)	(1.75)	(1.85)
TradeRate	0.0603***	0.0639***	0.0663***	0.0647***
	(5.89)	(6.38)	(6.54)	(6.40)
RnDRate	0.3651***	0.3884***	0.4871***	0.484***
	(4.97)	(5.40)	(5.32)	(4.35)
UrbRate	0.0168	0.0208**	0.0233**	0.0218**
	(1.73)	(2.20)	(2.43)	(2.32)
EnergyEffi	12.2071***	12.2929***	12.2945***	12.2836***
	(22.69)	(22.83)	(22.71)	(22.81)
City Fixed	No	No	No	No
Year Fixed	Yes	Yes	Yes	Yes
R^2	0.4802	0.4762	0.4732	0.4759
N	3043	3043	3043	3043

Note: ***, ** and * represent significance levels of 1 %, 5 % and 10 %, respectively.

Table 5
Benchmark regression results 2.

	CO_2Eff	CO_2Eff	CO_2Eff	CO_2Eff
	(5)	(6)	(7)	(8)
Green bond	5.545***			
	(5.20)			
Green support		4.658***		
		(8.73)		
Green fund			1.311***	
			(9.48)	
Green equity				1.925***
				(9.48)
IndRate	0.0367	0.0293	0.0425	0.0312
	(1.38)	(1.17)	(1.67)	(1.21)
TradeRate	0.0678***	0.0664***	0.0645***	0.0663***
	(6.43)	(6.57)	(6.24)	(6.37)
RnDRate	0.3950***	0.3754***	0.3830***	0.3961***
	(5.33)	(5.08)	(5.23)	(5.52)
UrbRate	0.0227**	0.0250**	0.0234**	0.0243**
	(2.4511)	(2.4373)	(2.28)	(2.42)
EnergyEffi	12.2821***	12.3422***	12.2336***	12.2431***
	(22.77)	(22.76)	(22.53)	(22.57)
City Fixed	No	No	No	No
Year Fixed	Yes	Yes	Yes	Yes
R^2	0.469	0.470	0.474	0.473
N	3043	3043	3043	3043

Note: *** and ** represent significance levels of 1 % and 5 %, respectively.

for verifying the reliability and stability of the main regression findings, ensuring that the conclusions hold under different conditions and data treatments.

Shrinking method (Column 1): Carbon emission efficiency is reduced by 1 % to mitigate the potential impact of outliers on the regression results.

Replacement of the explanatory variables (Column 2): This method is utilized to reevaluate the green finance index, resulting in a new index. Subsequently, regression analysis is performed with this new index as an explanatory variable to assess the consistency of the results.

Endogeneity test (Column 3): An endogeneity test is conducted to account for possible mutual causation and omitted variables. The green finance index, with one lag and two lags, is utilized as instrumental variables (IVs). The results of the over-identification test and

Wald F test indicate the validity of the constructed two-stage regression model, affirming the absence of endogeneity in the selected instrumental variables.

Clustering method (Column 4): Principal component analysis (PCA) and k-means clustering are employed to cluster the data into two categories. After clustering, outliers are removed. Subsequent regression analysis is conducted to determine whether the results remain consistent after the removal of outliers.

The results are shown in Table 6 and Fig. 1. The coefficients directions of the green finance index remain consistent with the benchmark regression results. All these coefficients pass the significance test at a significance level of 0.01. Consistency between different robustness test methods increases confidence in the reliability and robustness of benchmark regression results. The relationship between the green finance index and carbon emission efficiency is robust and holds up under various test methods, further affirming the validity of our conclusions.

5.3. Heterogeneity analysis

The division of the sample regression into the eastern, central, and western regions allows the analysis of regional heterogeneity in the impact of green finance on carbon emission efficiency. The regression results for each region are shown in columns (1), (2), and (3) in Table 7, respectively.

Eastern region: The green financial index in the eastern region passes the significance test at a 0.05 level. The regression coefficient is positive, indicating that green finance has a positive impact on carbon emission efficiency in the eastern region. The higher degree of industrialization and energy consumption in eastern region, along with greater economic development and per capita income, contribute to the positive effects of green finance on carbon emission efficiency.

Central region: Similar to the eastern region, the green financial index in the central region also passes the significance test at a 0.05 level. The coefficient is positive, suggesting a positive impact of green finance on carbon emission efficiency. The central region benefits from its industrial base, resource advantages, and favorable environmental conditions, which facilitate the development of green industries and the effectiveness of green financial policies.

Western region: In the western region, the green financial index also passes the significance test at a 0.05 level. The coefficient is positive, indicating the positive relationship between green finance and carbon emission efficiency. The relatively fragile ecological environment, dominance of resource-based industries, and remote geographical location in the western region pose challenges to the promotion and application of green finance. However, financial support and the emerging green industry contribute to improved carbon emission efficiency.

The analysis of control variables further reveals regional differences. The impact of total import and export as a share of GDP on carbon emissions varies across regions, with positive effects in the eastern region and negative effects in the western region. R&D expenditures as a share of GDP show varying significance and direction across regions, reflecting differences in industrial structures and development stages. Urbanization rate has a significantly positive impact on carbon emission efficiency in the eastern region. These regional variations highlight the complexity of factors influencing carbon emission efficiency, with economic development, industry composition, and regional characteristics playing distinct roles in different areas of China.

5.4. Threshold effect analysis

This paper establishes a threshold panel model to explore the nonlinear characteristics of the impact of green finance on carbon emission efficiency at different stages of GDP development. Through 500 times Bootstrap repeated sampling, the results are shown in Table 8 and Table 9.

The results suggest that there is a nonlinear relationship between GDP and the impact of green finance on carbon emission efficiency. At low GDP stage (GDP $<$827.4320), the effect of green finance on carbon emission efficiency is not pronounced. This may imply that when a country or region is in the early stages of economic development (low GDP), there might be other pressing economic concerns that take precedence over environmental considerations. At high GDP stage (GDP $>$827.4320), the effect of green finance on carbon emission efficiency becomes more significant. This suggests that as a country's or region's economy becomes more developed,

Table 6
Robustness test results.

	Shrinkage	Replace explanatory variables	IV	k-means clustering	k-means clustering	k-means clustering
	(1)	(2)	(3)	(4)	(5)	(6)
GFinaDEX	0.3175***		0.1341***	0.3521***	0.3175***	
	(18.35)		(3.93)	(15.61)	(18.35)	
RSR		0.2086***				0.2086***
		(12.62)				(12.62)
Control	Yes	Yes	Yes	Yes	Yes	Yes
City Fixed	No	No	No	No	No	No
Year Fixed	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.4753	0.4784	0.4371	0.4752	0.4753	0.4784
N	3043	3043	3043	3004	3043	3043

Note: *** represents significance levels of 1 %.

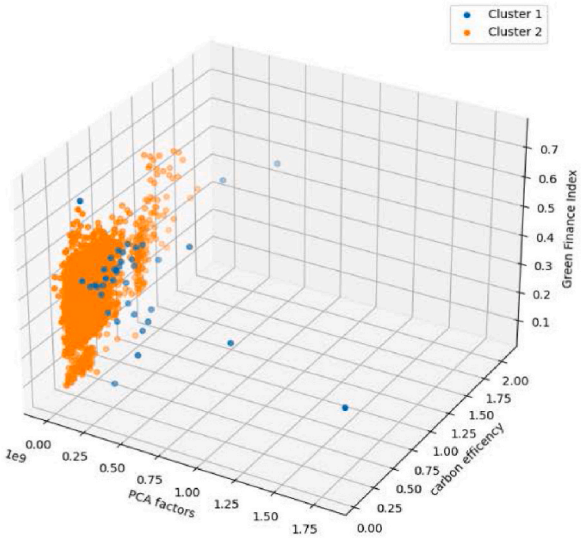

Fig. 1. K-means clustering results.

Table 7
Heterogeneity analysis results.

	Eastern	Central	Western
	(1)	(2)	(3)
GFinaDEX	1.1107***	0.4945***	0.0691**
	(6.5503)	(8.1042)	(2.2349)
IndRate	0.3327***	0.0385**	0.2382**
	(3.9282)	(2.5282)	(2.7344)
TradeRate	0.0447***	−0.0081	−0.0535***
	(3.3749)	(-0.1662)	(-3.1842)
RnDRate	1.1270***	−0.1193*	0.1073**
	(4.6326)	(-1.7475)	(2.3937)
UrbRate	0.0413*	0.0284	0.0002
	(2.0304)	(1.6485)	(0.0152)
EnergyEffi	11.6390***	11.2633***	12.5573***
	(13.3538)	(43.1969)	(14.2014)
City Fixed	No	No	No
Year Fixed	Yes	Yes	Yes
R^2	0.447	0.580	0.568
N	1309	1088	646

Note: ***, ** and * represent significance levels of 1 %, 5 % and 10 %, respectively.

Table 8
Threshold effect test.

Threshold variables	Threshold type	Threshold value	p-value	Variable value
SC	Single threshold	827.43	0.0660	GDP≤827.43
	Double threshold	5206.90	0.1860	827.43 ≤ GDP≤5206.90

the role of green finance becomes increasingly important in improving carbon emission efficiency. Furthermore, the marginal effect of green finance is increasing in the high GDP stage, indicating that the benefits of green finance in reducing carbon emissions become even more pronounced as the economy develops further.

These findings have important policy implications. Promoting green finance initiatives and policies may be particularly effective in countries or regions with higher levels of economic development, as it becomes a key driver in enhancing carbon emission efficiency. However, in the early stages of economic development, other economic priorities may take precedence, and the impact of green finance on carbon emissions may be less apparent.

The results of likelihood ratio (LR) test from the threshold regression are shown in Fig. 2.

Table 9
Threshold model regression results.

Threshold interval	(1)
$GFinaDex_{it}(GDPPC_{it} \leq 2.8139)$	0.2828***
	(8.65)
$GFinaDex_{it}(2.8139 \leq GDPPC_{it} \leq 3.8867)$	0.4371***
	(12.58)
Control variables	Yes
City Fixed	No
Year Fixed	Yes
R^2	0.5012
N	3043

5.5. Intermediary effect analysis

In order to reveal the mediating role of innovation in the impact of green finance on carbon emission efficiency, we select the number of patents granted as the mediating variable in the construction of the mediation regression model after 5 % shrinking of the variable to remove outliers, and the regression results are shown in Table 10. Seen from Column (2), the development of green finance can significantly increase the number of patent applications. After adding mediator variables in Column (3), the coefficient of green finance on carbon emission is still significantly positive, and the coefficient becomes smaller compared with Column (1), indicating that there is a mediation effect of innovation with the value 0.04562. The direct effect of digital financial inclusion is 0.2940, and the intermediary effect accounts for 5.38 % of the total effect. The results are consistent with previous research [14,15]. Seen from the results of the correlation test, the Sobel test p-value is 0.0320, which also indicates that the model does have a significant partial mediation effect. The possible reasons are as follows.

Firstly, innovation plays a pivotal role in improving the quality of environmentally friendly financial products. Green finance has emerged as a crucial financial instrument, offering environmentally friendly products and services. It serves as a catalyst for achieving integrated economic, social, and environmental development in investments. Innovation serves as a valuable tool in helping green financial products meet consumer requirements and enhance their quality and performance. It facilitates the creation of more efficient, convenient, flexible, and sustainable products and services. This boosts the market share and attractiveness of green financial products and expedites the promotion and adoption of environmentally friendly products, among other benefits.

Secondly, innovation holds the key to enhancing the efficiency of green finance. One of the foremost challenges facing green finance is the reduction of costs associated with environmentally responsible products, while simultaneously increasing their economic effectiveness. Innovation plays a pivotal role in addressing this challenge by enabling the more efficient and cost-effective utilization of existing technologies and resources within green finance.

Thirdly, innovation is a catalyst for the growth of green finance. To meet the rising consumer demand for environmentally friendly products and services, the expansion of the green finance market necessitates continuous innovation and progress. Innovation serves as

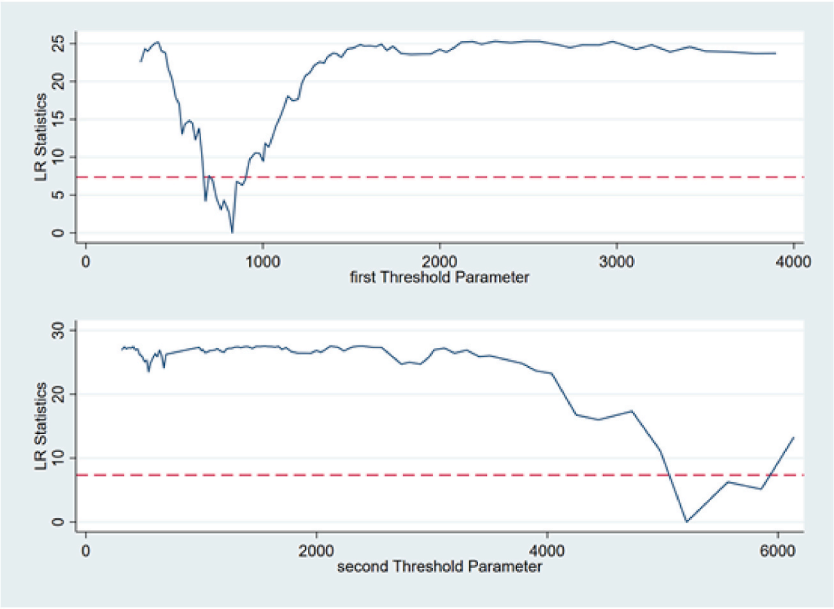

Fig. 2. LR statistics for threshold effect.

Table 10
Regression results of intermediate effects.

	CO_2Eff	*PatCnt*	CO_2Eff
	(1)	(2)	(3)
GFinaDEX	0.2940***	1.0812**	0.2781***
	(14.65)	(2.81)	(13.92)
PatCnt			0.0146***
			(3.31)
Control variables	Yes	Yes	Yes
City Fixed	No	No	No
Year Fixed	Yes	Yes	Yes
R^2	0.484	0.388	0.492
N	3043	3043	3043

Note: *** and ** represent significance levels of 1 % and 5 %, respectively.

the driving force behind broadening opportunities and choices within the green finance sector, facilitating its development and enlargement. Innovation can pave the way for the creation of new financial products and services tailored to the diverse requirements of investors and markets. It can also introduce fresh technologies and resources, enhancing the investment appeal and market competitiveness of green finance. Furthermore, innovation is instrumental in addressing emerging environmental protection and sustainable development challenges, establishing a robust foundation for the long-term development of green finance.

In summary, it is imperative for innovation to play a pivotal role in the realm of green finance to advance carbon efficiency. Innovation has the potential to elevate the quality of green financial products, amplify the effectiveness of green finance, and drive the expansion of this sector. Consequently, this synergy empowers green finance to more efficiently curtail carbon emissions. The interplay between green finance and innovation is mutually reinforcing and holds the potential to make substantial contributions to the enduring progress of the environmental and sustainable development sector.

5.6. Sensitivity analysis

This paper constructs a random forest machine learning model incorporating independent variables including green credit, green investment, green insurance, green bond, green support, green fund, green equity, urbanization level, industrial structure, openness, innovation level, energy utilization, and changes in the green inclusive finance index at each stage. The dependent variable in this model is carbon emission efficiency. Following the acquisition of training results, the paper calculates partial derivatives of the green finance index. These derivatives are employed to assess the sensitivity of carbon emissions to variations in green funding. The results are shown in Table 11.

The output has an MAE of 0.02, which is close to 0. R^2 is 0.962, which is close to 1. This indicates that the model fits well, and the comparison between the true and predicted values of its prediction set are shown in Fig. 3.

The predicted values fit the true values well, indicating that the model has a good prediction. The sensitivity curve of the output is shown in Fig. 4. The sensitivity of carbon emission efficiency exhibits an initial increase followed by a subsequent decline with the rise of the green financial index. This pattern can be attributed to several factors. The heightened sensitivity of carbon emission efficiency at lower green financial index values may be attributed to enterprises giving less attention to environmental protection in such instances, with fewer influencing variables affecting carbon emission efficiency. However, as the green financial index rises to a certain threshold, enterprises become more environmentally conscious. Simultaneously, the index incorporates a greater number of

Table 11
Random forest model training parameters.

Parameter name	Value	Description
N_estimators	100	Number of trees in a random forest
Criterion	MSE	Metrics for measuring split quality
Max_depth	None	Maximum depth of the tree
Min_samples_split	2	Minimum number of samples required for internal node division
Min_samples_leaf	1	The minimum number of samples required for a leaf node
Min_weight_fraction_leaf	0	The minimum weighted fraction required for a leaf node
Max_features	Auto	Number of features to be considered in finding the optimal segmentation
Max_leaf_nodes	None	Maximum number of leaf nodes
Min_impurity_decrease	0	Threshold to stop splitting
Bootstrap	TRUE	Whether to bootstrap sample or not
Oob_score	FALSE	Whether to use out-of-bag samples for model evaluation
N_jobs	None	Number of parallel jobs for training
Random_state	None	Control the seeds of random number generation
Verbose	0	Control the level of detail, the higher the value the more detailed the printed information
Warm_start	FALSE	Whether to use the last training result for initialization
Ccp_alpha	0	Parameters for Cost Complexity Pruning

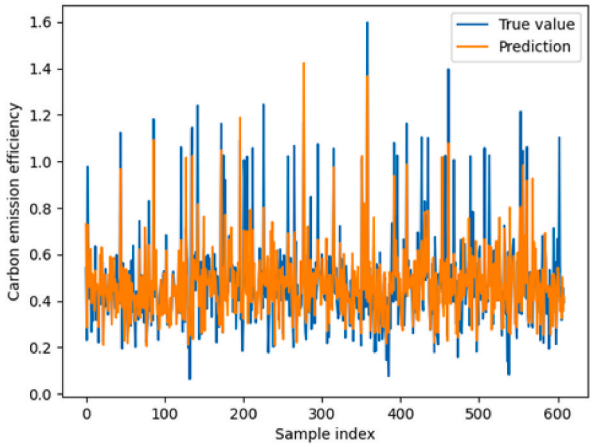

Fig. 3. Comparison of predicted and true values of random forest model.

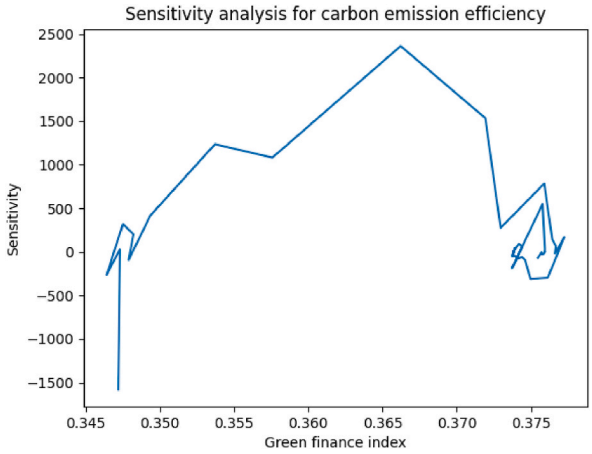

Fig. 4. Sensitivity analysis curve.

environmental protection factors. Consequently, further increases in the green financial index may introduce complexity in the factors influencing carbon emission efficiency, leading to a decrease in sensitivity.

In essence, as the green financial index increases, the determinants of carbon emission efficiency become more numerous and intricate. Enterprises are compelled to consider the individual impact of each component of the green financial index on the efficiency of carbon emission reduction in their decision-making processes. Moreover, due to the nonlinear relationship between the green financial index and carbon emission efficiency, its influence may exhibit contrasting trends at low and high index values, resulting in shifts in sensitivity.

In economies with a low green financial index, there exists the potential for a significant enhancement in carbon emission efficiency through its increase. This is because, in low-index situations, enterprises generally possess lower environmental awareness and technology levels. Conversely, in the case of a higher green financial index, the impact of further index increases on carbon emission efficiency may diminish. At this stage, enterprises already maintain higher environmental awareness and technology levels, and the incremental effect of increasing the green financial index on their environmental protection practices becomes limited.

5.7. Sub-dimension importance analysis

Understanding the significance of the various components of green inclusive finance in relation to carbon emission efficiency is pivotal for informing government policies aimed at fostering its growth. In this paper, we construct a long-term and short-term memory (LSTM) artificial neural network model. This model includes green credit, green investment, green insurance, green bond, green support, green fund, green equity, urbanization level, industrial structure, openness, innovation level, and energy utilization as independent variables, with carbon emission efficiency as the dependent variable. The training parameters are shown in Table 12.

The evaluation results obtained from training the model indicate a mean squared error (MSE) value of 0.01 and a root mean square error (RMSE) value of 0.08, both of which are nearly equal to zero. These values suggest an excellent fit of the model. The comparison

Table 12
Training parameters of LSTM neural network model.

Parameter name	Parameter value	Parameter explanation
Epochs	100	Number of training sessions
Batch_size	1	Number of samples selected for each iteration
Look_back	3	Number of time steps, length of each input sequence
Number of LSTM neurons	32	Number of hidden layer neurons
Len (feature_cols)	12	Model input feature dimension
Feature normalized range	(0, 1)	The range of values of the normalized features
Optimizer	Adam optimizer with default learning rate of 0.001	Algorithm for controlling model updates
Loss function	Mean Squared Error	Define the objective function for model optimization

between the actual and predicted values of the prediction set is illustrated in Fig. 5. The predicted values fit the true values almost perfectly, indicating that the model has excellent prediction. The output feature importance is shown in Table 13.

The feature importance ranking and the associated explanations shed light on the relative importance of different components within the green finance sub-dimension.

> Green equity occupies the top position because it directly involves equity investment. Companies can secure capital for environmental and sustainable development projects through the issuance of green equity. This type of investment encourages sustainable practices within companies and allows investors to participate in both environmental initiatives and capital returns.

Green insurance is ranked second due to its role in mitigating risks associated with environmental and sustainability projects. Such projects can face risks like natural disasters and environmental pollution. Green insurance offers investors a sense of security, thereby attracting more capital to support these projects and advance sustainable development.

Green funds hold the third position as they pool funds from multiple investors to support various environmental and sustainable development projects. This diversification helps reduce risk while offering investors diversified investment opportunities, furthering green development.

Green credit is fourth on the list as it supports sustainable business development through loan capital provision. While it plays a role in financially backing environmental projects, its impact is relatively limited because it involves loans and not equity investments.

Green support is ranked fifth, providing direct financial assistance. However, its impact is modest as it can fund environmental projects but lacks the diversified investment opportunities of green equity or green funds.

Green investment ranks sixth as it directly funds projects for environmental protection and sustainable development. Despite contributing to project financing, its impact is comparatively limited due to its usual exclusion of equity investments and higher associated risks.

Green bonds occupy the last position due to their stringent usage restrictions and extended investment cycles. Funds from green bonds can only be used in environmental protection and sustainable development areas, and the bonds generally have lengthy maturity periods and relatively lower returns. Consequently, green bonds have a limited scale of funds and influence on carbon emission efficiency compared to other green financial instruments.

These rankings provide valuable insights into the varying impacts of different green finance components on carbon emission efficiency, allowing for more informed policy and investment decisions.

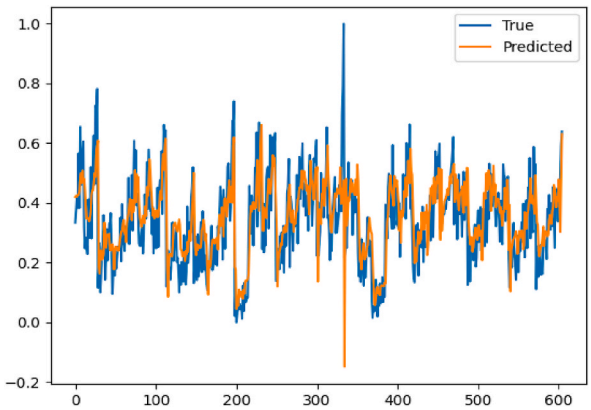

Fig. 5. Comparison of predicted and true values of LSTM neural network.

Table 13
Relative importance of features.

Variable	Relative importance (%)	Ranking
Green equity	17.42	1
Green insurance	14.45	2
Green fund	12.39	3
Green credit	9.59	4
Green support	6.06	5
Green investment	4.18	6
Green bond	0.07	7

6. Conclusions and policy implications

6.1. Conclusions

This paper utilizes data of prefecture-level cities in China from 2006 to 2022 and studies the promotion of green finance on carbon emission efficiency. The results reveal that both green finance and its seven sub-dimensions significantly contribute to improving carbon emission efficiency. The efficacy of green finance in reducing carbon emissions follows a geographical pattern, with the western, central, and eastern regions displaying increasing levels of effectiveness, respectively. The relationship between green finance and carbon emission efficiency exhibits nonlinear characteristics. This nonlinearity is influenced by distinct stages of GDP development. Specifically, there exists a GDP development threshold, resulting in a trend of increasing marginal effects of green finance. Moreover, the substantial partial mediating role played by innovation contributes approximately 12.56 % to the overall observed effect. As the green finance index increases, the sensitivity initially rises and then declines, forming an inverted U-shaped trend. Lastly, the sub-dimension importance analysis ranks the seven components of green finance in terms of their impact on carbon emission efficiency, with green support, green credit, green insurance, green investment, green equity, green fund, and green bond following in order of significance.

6.2. Policy implications

Government emphasis should be placed on the development of the green support and green credit sub-dimensions, given their substantial impact on carbon emission efficiency. It is necessary to encourage banks and financial institutions to expand their green credit services through fiscal incentives and tax reductions. However, prudent consideration of the risk management capabilities of these institutions is vital to ensure the sustainability and stability of green financing programs. Implement mechanisms to guarantee that the benefits of these policies directly contribute to improvements in carbon emission efficiency. Regulatory and supervisory mechanisms may be required to ensure that funds are genuinely channeled into green projects.

The central government should recognize the diverse economic, industrial, and environmental characteristics of different regions and formulate policies accordingly. It is beneficial to collaborate closely with local governments and stakeholders to tailor policies to regional needs and potential. Coordination mechanisms between regions should also be established to prevent conflicts and inconsistencies between different policies.

Local government should acknowledge the vital mediating role of innovation in the relationship between green finance and carbon emission efficiency. It is necessary to enhance the role of green finance by supporting R&D in green technologies and foster innovation to enhance the innovativeness of financial products and services. A balanced approach between innovation and risk management should be maintained to ensure that innovation does not jeopardize financial stability or environmental risk.

Local government should recognize the existence of the threshold effect related to the stage of GDP development and its impact on green finance. Local government should formulate policies tailored to the GDP level of each region to ensure policy applicability and effectiveness. It is beneficial to consider potential distributional and social equity issues that may arise from linking policies to GDP levels and strive for a balanced approach.

Governments have the potential to enhance green financing and carbon efficiency through a well-crafted policy framework that includes differentiation, innovation support, strengthened regulation, and consideration of social equity. However, policymakers must carefully assess potential challenges and constraints during policy development and implementation to ensure long-term sustainability and success. Additionally, the outcomes and impacts of these policies should be continually assessed to provide enterprises and policymakers with guidance and insights for future endeavors.

6.3. Limitations and further research

This paper has several limitations. Future research may incorporate a more comprehensive assessment of external factors, including international market dynamics, global economic fluctuations, and the evolution of policy formulation. These factors can significantly influence carbon emission efficiency and should be examined more thoroughly to provide a holistic understanding.

The proposed policy recommendations require further in-depth analysis to assess their actual impacts on carbon emission efficiency. Future research should delve into the specific effects of different policy measures to offer more precise and actionable recommendations. To ensure consistency and comparability in research results, it is essential to provide a clearer definition of green

finance, both regionally and temporally. Given the vast geographic and economic disparities within China, future research should conduct more extensive regional analyses. This approach would yield deeper insights into the differential impact of green finance on carbon emission efficiency across various regions.

In summary, future research should strive to address these limitations and contribute to a more comprehensive understanding of carbon emissions. Expanding the analysis scope to encompass external factors, conducting detailed policy impact assessments, refining the definition of green finance, and exploring regional differences will enhance the overall knowledge base in this critical field.

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Author contribution statement

Yueling Cai: Writing – review & editing, Writing – original draft, Project administration, Formal analysis. Xu Liu: Software, Methodology, Data curation. Gongliang Wu: Writing – review & editing, Writing – original draft, Software, Formal analysis, Data curation, Conceptualization

Data availability statement

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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