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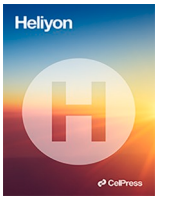

Influence mechanism of green finance on regional emission reduction

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A R T I C L E I N F O

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A B S T R A C T

The implementation of green finance is crucial in achieving a reduction in regional emissions. As such, understanding how green finance affects regional emission reduction is essential. Using provincial panel data from 2008 to 2019, we employed the fixed effects model to examine the impact of green finance on regional emission reduction. The empirical results reveal the following: (1) Green finance has a negative effect on sulfur dioxide intensity, and the development of green finance can significantly reduce the emission of regional pollutants. (2) Among the different instruments of green finance, green credit and green investment exhibit more substantial emission reduction effects than green securities and green insurance. (3) The mechanism by which green finance affects regional emission reduction is mainly through the advanced industrial structure and green technology innovation. (4) The development of green finance shows geographical discrepancies: The eastern region of China is more effective in reducing emissions than the central and western regions. To fully maximize the role of green finance in emission reduction, this paper offers pertinent suggestions for strengthening the green financial system, improving the advanced industrial process, increasing investment in green energy technology, and formulating specific development tactics that consider the prominent characteristics of distinct regions.

1. Introduction

Since the policy of reform and opening-up, under the influx of population, capital, and other factors, China's economy has retained a long-term high-speed enhancement. However, environmental problems have become increasingly prominent. Air pollution has become more severe, and the excessive exploitation and use of water and mineral resources and the indiscriminate discharge and accumulation of pollutants continue to seriously threaten the development of China's green economy. Addressing the issue of environmental protection while promoting economic development is a current focal point of society and research. Resource conservation and environmental protection are inseparable. Energy conservation and consumption reduction can alleviate the pressure on energy resources and bring about environmental and economic benefits to a certain extent. The "14th Five-Year Plan" Comprehensive Work Plan on Energy Conservation and Emissions Reduction specifies that by 2025, the energy consumption per unit of GDP nationwide should be reduced by 13.5 % compared with 2020. The total emissions of chemical oxygen demand, ammonia nitrogen, nitrogen oxides, and volatile organic compounds should be reduced by more than 8 %, 8 %, 10 %, and 10 %, respectively, compared with 2020.

Prompt actions toward the transformation and development of heavily polluting enterprises are imperative, as they are significant

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sources of pollution emissions. Encouragement is needed to adopt clean energy to substitute for the usage of fossil fuels in production processes for reduced pollution emissions and to promote eco-friendliness. Currently, concerns for green economic development and environmental protection have intensified. The optimization of industrial, energy, transportation, and other structures are beneficial for green production processes and lifestyles. The promotion of green finance are essential in driving China's industrial restructuring efforts and fostering sustainable and wholesome economic growth. Simultaneously, this approach underscores the importance of prioritizing environmental protection as a critical aspect of long-term economic development [1]. Correspondingly, green finance serves as a significant approach for pollution reduction and environmental protection, the optimization of energy conservation, and emission reduction industries. However, it may also somewhat counteract green finance [2]. Hence, exploring the influence of green finance on regional emission reduction aligns with the trend of the times and holds great significance for the advancement of China's construction.

The principal objective of this research is to test the influence of green finance on regional emission reduction and provide answers to the following questions. First, does the growth of green finance effectively reduce pollutant emissions in China? Second, among the secondary indicators of green finance, which indicator significantly influences emission reduction? Third, what is the influence mechanism supposing that green finance decreases pollutant emissions? Last, is there a significant variance in the influence of green finance regarding emission reduction among different regions in China? In pursuit of these answers, this paper uses fixed-effects model to examine the relationship between the green finance index and regional emission reduction with provincial panel data from 2008 to 2019. Additionally, the research explores the mechanism underlying the influence of green finance on regional emission reduction. It investigates the heterogeneity of the role of green finance in emission reduction across the eastern, central, and western regions.

The master contributions are as follows: First, considering the severity and urgency of pollutant hazards, sulfur dioxide is selected as the indicator of regional emission reduction, while carbon dioxide is utilized as the pollutant indicator in the robustness test. Second, the research applies the entropy value method to derive the green finance index, which includes the emission reduction effect of green finance and the secondary indicator of green finance independently. It enriches green finance tools, mitigating the inadequacies in discussing green finance and regional emission reduction.

The limitation of the paper is mainly related to the data. First, the research data are not updated to the latest. However, inter-provincial data before 2019 are helpful to avoid the impact of COVID-19. Second, conducting research at the provincial level is prone to overlooking imbalances within provinces, which is a direction for further research based on county-level data.

This paper framework is as follows: Section 2 provides an overview of the literature; Section 3 conducts theory and hypothesis; Section 4 describes the research design; Section 5 analyzes the regression results, including the primary regression analysis, heterogeneity analysis, influence mechanism, and robustness test; Section 6 concludes and recommends.

2. Literature review

2.1. Regional emission reduction

The promotion of the green development model has sparked widespread attention to pollution reduction. The development of the digital economy can significantly lower carbon emissions, and this effect is more pronounced in nonresource-based cities and eastern regions [3]. Based on China's prefecture-level cities' data, economic growth primarily drives cities' low-carbon transformation through energy efficiency, green technology, and industrial upgrading [4]. The optimized regional industrial structures are favorable for pollution reduction and create spatial spillover. Upgraded industrial structures in neighboring regions also reduce local pollution emissions [5].

Furthermore, environmental regulations can moderately decrease air pollutant emissions, but the relationship is nonlinear. The degree of environmental regulations' impact on air pollution is not strictly increasing or decreasing. However, it depends on regional economic growth levels where economic growth within a specific range under environmental regulations is more effective [6]. In addition, the relationship between population agglomeration and per capita carbon emissions follows an inverted N pattern, with most provinces currently in the first stage [7], which indicates substantial potential for promoting emission reduction through population agglomeration. As green finance combines finance and the environment, in recent years, the emission reduction effect of green finance has received the attention of many scholars, and many scholars have also discussed its effect on emission reduction.

2.2. Green finance and regional emission reduction

Green finance has reduced air and water pollution and curated carbon dioxide emissions [8]. It is crucial in supporting green transformation and facilitating carbon peak and carbon-neutral processes [9–12]. Establishing green finance reform pilot zones can considerably inhibit local carbon emission reduction [13,14] and improve social responsibility fulfillment, technological innovation of enterprises, and low-carbon transformation of high-emission companies [15]. The upgrading of industrial structures and energy consumption structure transformation may also nurture pollution reduction effects [16–18]. Green credit has emerged as a mature green finance tool, with numerous studies focusing on its emission reduction effects. Green credit policy can significantly reduce agricultural carbon emissions in agriculture by establishing resource allocation utility, technology innovation utility, and signaling utility pathways [19]. Using sulfur dioxide emissions and soot emissions as explanatory variables, we found that green credit instruments had a suppressive effect on both types of pollutants, which was more substantial among highly polluting industries, large-scale companies, and enterprises facing low regional development pressure [20]. In addition, when considered separately, green credit and green venture capital significantly reduced carbon emissions. However, combined into the same model, the green venture

capital coefficient was no longer significant [21]. This outcome indicates that the emission reduction effect of green credit may be superior to that of green venture capital.

In general, the existing research pays more attention to the effect of green finance and the influencing factors of regional emission reduction. Moreover, most studies pay more attention to the effect of green finance on carbon emissions reduction while paying less attention to other pollutant emissions. When evaluating green finance, many scholars use green finance policy as a quasi-natural experiment or synthesize a green finance index by selecting secondary indexes, with few studies exploring the emission reduction effect of each secondary index except for green credit. As such, this paper focuses on sulfur dioxide as the primary pollutant, with the core explanatory variables being the green finance index and each secondary index of green finance. Specifically, the paper examines and compares the emission reduction effects of green credit, securities, investment, and insurance as separate explanatory variables.

3. Theory and hypothesis

3.1. Impact of green finance on regional emission reduction

Green finance encompasses diverse economic activities to improve environmental conditions, mitigate climate change, and promote efficient resource utilization. It targets environmental protection, clean energy, energy conservation, green transportation, and other related areas. To date, there is no universally agreed-upon conclusion about the impact of green finance on emission reduction. However, most scholars concur that green finance can potentially reduce pollution emissions. It could restrict investments in energy-intensive industries while strengthening investment in technology-intensive industries, bringing about industrial restructuring and environmental protection [22]. Empirical analyses utilizing panel models, spatial Durbin models, and double difference models, among others, have found that increasing levels of green finance can effectively control environmental pollution [23–25]. However, green finance has no simple linear relationship with emission reduction. There exists a threshold of green finance development that promotes industrial pollutant emissions at first and only achieves a suppressive effect once pollutant emissions reach a certain level [18]. Moreover, economic growth and carbon emissions follow an inverted-N pattern. China is currently in the second stage of the rise, making green finance's carbon emissions inhibitory role significant [26].

Regarding the emission reduction effect of each secondary indicator, most scholars believe that the emission reduction effect of green credit is the most obvious, and there is less discussion on other secondary indicators. Among them, green credit can play a role in pollution emissions directly and indirectly [27]. This view has also been endorsed by other scholars, who believe that green credit can effectively inhibit carbon emissions, specifically manifested in significantly increasing total factor carbon productivity and reducing carbon emission intensity [28]. There is a lack of discussion among scholars regarding the emission reduction effect of green securities. Some scholars affirm the progress of the development of green securities in recent years in their paper but also point out that green securities are still characterized by the problems of inconsistent indexes and asymmetry of information, which may affect the emission reduction effect of green securities. China's green securities mainly focus on environmental verification in the early stages. However, there is no continuous study during the later operation period [29,30].

Regarding green investment, China's total investment in pollution control and environmental protection expenditures shows a perennial growth trend, fully reflecting the government's concern with environmental issues. The more the government invests in the environment, the more beneficial it is for pollution treatment. In terms of green insurance, since the implementation of environmental liability insurance by enterprises in China is relatively late and the data are relatively scarce, considering that agriculture is most susceptible to the influence of the natural environment, the proportion of agricultural insurance scale and agricultural insurance payout rate roughly represent the growth of green insurance in China [31]. The scholar explored the impact of agricultural insurance on agricultural carbon emissions, pointing out that agricultural insurance significantly contributes to reducing total agricultural carbon emissions [32]. Therefore, based on the above analysis, the first hypothesis is proposed in this paper.

H1. Green finance exerts significant suppressive effects on regional emissions.

3.2. Impact mechanism of green finance on pollution reduction

At present, the discussion of green finance on regional emission reduction mechanisms mainly focuses on advanced industrial structure [33,34], the structure of energy consumption [16], resource allocation effect [35], improvement of environmental regulation [13], and so on [36–38]. However, this paper argues that the most prominent role of green finance is the reallocation of financial resources, that is, the continuous injection of green funds into the environmental protection industry, limiting the financial availability of polluting industries. First, China faces an essential industrial transformation period. Industrial structure adjustment is more drastic, and the impact of green finance on pollution emissions is more pronounced. Second, China pays increasing attention to environmental regulation and encourages enterprises' continuous technology innovation. At the same time, advanced emission reduction technology has become essential for enterprises to establish a foothold in the market, which can directly inhibit the pollution emissions of enterprises. Therefore, this paper mainly discusses the impact of green finance on regional emission reduction from the perspectives of the advanced industrial structure and green technology innovation.

3.2.1. Advanced industrial structure

The advanced industrial structure pertains to a country's transformation from labor-intensive to knowledge-intensive and technology-intensive industries. An industry's advancement level is widely believed to correspond to its environmental impact

directly. Long-term and stable cointegration relations have been observed between industrial structure and pollution emissions [39]. Financial support is crucial in promoting the advanced industrial structure, with banks and capital markets facilitating the flow of considerable capital into enterprises to provide support [40]. Green finance plays a significant role in resource allocation, with emerging environmental protection industries gaining access to sufficient funds, promoting new industries' development, and providing clear advantages.

Meanwhile, the "two high and one leftover" industries, which are more polluting, will face strict financing restrictions, increasing their cost and pressure to transform and upgrade [41]. Client enterprises' environmental responsibility is assessed when approving loan projects, and a different interest rate policy is applied. Financial restrictions on the "two high and one leftover" industries deprive them of funding and add enormous environmental pressure, making it hard to maintain their current growth trends. They are thus obliged to transform into industries with low-pollution emissions. In capital market financing, the green industry exhibits more pronounced advantages. As the general public increasingly embraces green and low-carbon lifestyles, the green industry's future seems more promising. As a result, investment in green industry is more inclined, leading to inevitable industrial structure improvement. Therefore, the second hypothesis is as follows.

H2. The impact of green finance on reducing regional emissions is closely linked to the advanced industrial structure.

3.2.2. Green technology innovation

Innovation is the primary source and driving force behind enterprise development. In green finance, enterprises face the dual pressure of external regulation and internal product renewal. It has increased the willingness to invest in green technology innovation, especially for heavily polluting firms. Increased investment in green technologies can improve core competitiveness and resource use efficiency, and reduce pollutant emissions [42]. Green finance provides lower financial support for green production enterprises, thus leading them to raise their innovation investment to reduce energy consumption and pollutant emissions per unit, which substantially affects pollutant emissions [43,44]. Despite green technology innovation, the long cycle of corporate innovation activities, the high investment threshold, and uncertainty in success are significant barriers that prevent some companies from investing technology innovation [45]. The development of green finance addresses these financing constraints by providing preferential financial support for firms undertaking environmental and innovation investments [46]. Increasing investment in green technology innovation is an essential embodiment of corporate social responsibility, and competition among companies now extends beyond operational capabilities to include corporate social responsibility as an essential factor for investors [47]. Companies undertaking green technology innovation relay positive business signals to the outside world, sending favorable news to the capital market [48]. As the input and output for green technology innovation increase, raw material consumption in production will gradually decrease, efficiency will improve, and operating costs will decrease [49]. The adoption of efficient production processes that prioritize the reduction of raw material consumption can significantly curtail pollutant emissions during production activities, thereby promoting the conservation of energy and safeguarding the environment. Concerning the above findings, we formulate the third hypothesis of this paper.

H3. The impact of green finance on reducing regional emissions is closely linked to adopting green technology innovation.

Fig. 1 shows the theoretical framework of this paper.

4. Research design

4.1. Variables

This paper's dependent variable is sulfur dioxide intensity, and the core explanatory variable is the green finance index. This paper introduces other factors affecting sulfur dioxide intensity as control variables in the model. The selected variables are as follows.

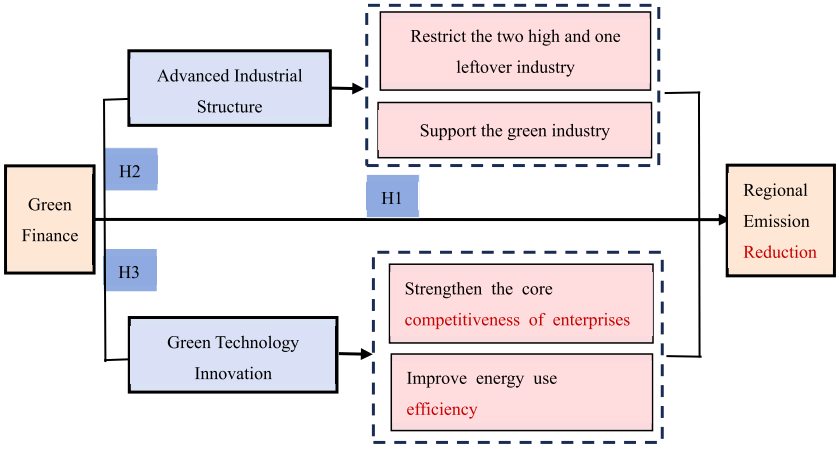

Fig. 1. The mechanism of green finance impact on regional emission reduction

1. Dependent variable. This paper examines the impact of green finance on regional emission reduction. This paper considers sulfur dioxide as an essential pollution monitoring indicator for the selection of pollutant measurements. First, some scholars have studied the relationship between green finance and carbon dioxide, and second, considering that although sulfur dioxide and carbon dioxide are air pollutants, their environmental harm is very different. As the main component of the atmosphere, carbon dioxide is also a greenhouse gas. It mainly causes the greenhouse effect by burning oil, coal, natural gas, etc., causing global warming and affecting climate change. Sulfur dioxide is a toxic gas that can pollute soil and water through the atmosphere, form acid rain, destroy plant growth, and endanger human health. The harm of sulfur dioxide is more severe than that of carbon dioxide. This paper selects sulfur dioxide intensity (SO2/GDP) as the dependent variable for each province to measure the degree of pollution reduction [20,50]. The robustness test replaces the explained variable with carbon dioxide intensity, and the result is not essentially different from that of sulfur dioxide, which further illustrates the rationality of choosing sulfur dioxide as the pollution monitoring index.
2. Core explanatory variables. Measuring the green finance index remains a contentious topic in the academic community, and there is no universal standard for such measurement. This paper follows the practice of selecting a primary indicator of the green finance index and setting four secondary indicators, namely, green credit, green securities, green investment, and green insurance [51]. Suitable tertiary indicators are chosen to measure the secondary indicators, and the entropy value method is used to assign objective values to each variable. The green finance index is the sum of the different indicator weights and is used as core explanatory variable. Notably, the carbon finance trading market in China is not sufficiently mature. It plays a minor role in green finance, so this paper has excluded it. Table 1 shows the specific evaluation system.
3. Control variables. Based on the literature, six variables are selected as control variables: GDP per capita, technology level, openness level, government involvement, population density, and marketization level. First, GDP per capita. As China's economy progresses into a stage of high-quality development, people's demand for the environment and quality of life is increasing. They increasingly prefer a lifestyle with less polluting emissions. Second, the technology level affects the efficiency of energy use. Technological advancement can reduce energy consumption while being environmentally friendly. The level of foreign opening is the third control variable. Foreign direct investment is converted into billion yuan and divided by GDP. There are two hypotheses, "pollution sanctuary" and "pollution halo." The former suggests that foreign investment brings environmental damage, while the latter believes they take technological advancements. Fourth, government involvement, constructed as local government budget expenditure divided by GDP, has a two-sided effect on environmental protection. With increased government spending, environmental protection can improve, including reducing sulfur dioxide intensity. However, environmental protection is often carried out by the government due to the negative externalities of the environment. It allows pressure to ease on environmental governance for heavily polluting enterprises. However, public expenditure on environmental protection may lead to heavily polluting enterprises increasing pollution emissions as they rely on government compensation to maintain their profit. Fifth, population density affects environmental pollution as greater population density entails higher energy consumption and increased pollution emissions. Last, the marketization level has garnered attention in recent years. China acknowledges the importance of market mechanisms in environmental protection and effectively engages all parties involved to achieve regional emission reduction.
4. Mediator variables. Two mediator variables are chosen based on theoretical analysis: advanced industrial structure and green technology innovation. First, the advanced industrial structure quantifies the progression from a lesser to a higher-level state in the region's industrial development, computed as the tertiary industry's added value divided by the secondary industry's added value. Second, the paper utilizes LNGTI to discern the extent of green technology innovation in various regions of China. The total figure of green invention patents and green utility model patents from each province is augmented by adding one before being subjected to a natural logarithm function. This variable is a reliable gauge of the degree of eco-friendly technological innovation across regions in China, with higher values signifying advanced technological innovations.

4.2. Model

China has implemented a green finance policy since 2007, green financial tools have been enriched, and the green financial development system has been improved. Considering that there is a lag in the green finance index, this paper selects the data of 30 provinces in China from 2008 to 2019, takes regional emission reduction as the research focus, conducts research with the object of

Table 1
Evaluation indicators of green finance.

First Indicator	Secondary Indicators	Tertiary Indicators	Variable Definition
Green Finance Index	Green Credit	Percentage of interest expenses in non-energy consuming industries	1 - Six high-energy-consuming industries' interest expense/total interest expense of industrial industries
	Green Securities	Percentage of the market capitalization of non-energy consuming industries	1 - Total market capitalization of six energy-consuming industries/ Total market capitalization of A-shares
	Green Investment	Environmental management pollution investment ratio	Total investment in pollution control/GDP
		Energy saving and environmental protection public expenditure ratio	Environmental fiscal expenditure/total fiscal expenditure
	Green Insurance	Agricultural insurance payout ratio	Agricultural insurance expenditures/agricultural insurance payouts

green finance, and constructs the model.

$$LNSO2_{it} = \alpha_0 + \alpha_1 GR_{it} + \alpha_n CONTROLS_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (1)$$

where i represents provinces and t denotes year. $LNSO2_{it}$ represents the sulfur dioxide intensity of province i in year t, and GR_{it} is the core explanatory variable, which represents the green finance index of province i in year t. $CONTROLS_{it}$ represents the control variables of province i in year t. μ_i is the fixed utility at the provincial level, δ_t is the time-fixed effect, and ε_{it} is the random disturbance term. α_0 is the intercept term, and α_n denotes the coefficient of each control variable.

The following model was utilized to establish the mediating effects:

$$M_{it} = \beta_0 + \beta_1 GR_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (2)$$

$$LNSO2_{it} = \gamma_0 + \gamma_1 GR_{it} + \gamma_2 M_{it} + \gamma_n CONTROLS_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (3)$$

where M_{it} represents the mediator variables of province i at year t. β_0 and γ_0 are the intercept terms, and γ_2 denotes the coefficient of each mediator variable. Other variables and parameters are defined in model (1).

4.3. Data

The impact of green finance on regional emission reduction was examined in this paper using panel data encompassing 30 provinces in China from 2008 to 2019. The data for the core explanatory variable of green credit are obtained from the China Industry Statistical Yearbook and Economic Census Bulletin. The share of green securities is sourced from the China Stock Market Accounting Research. In contrast, the share of investment in environmental treatment and pollution originates from the China Statistical Yearbook of Environment and China Statistical Yearbook. The Yearbook of China's Insurance provides the data for green insurance, and the share of public expenditure on energy conservation and environmental protection is obtained from the National Bureau of Statistics. The dependent variables are obtained from the National Bureau of Statistics, and the control variables, including the actual utilization of foreign direct investment, are obtained from the Statistical Yearbook of each province. The average exchange rate per year is obtained from the Statistical Communique of National Economic and Social Development, the marketization index is obtained from the China Market Index Database, and the rest of the control variables are obtained from the National Bureau of Statistics. The mediator variables of the advanced industrial structure are from the National Bureau of Statistics and the Green Technology Innovation Data from the China Research Data Service. The descriptive statistics of the main variables are shown in Table 2.

As shown in Table 2, after taking the logarithm, the mean value of sulfur dioxide intensity is 3.169, while the standard deviation is 1.398. Fluctuations in the data are reduced. The mean value of the green finance index is 0.321, which indicates an overall low level of green finance development, as it does not reach 0.5. The standard deviations of other control and mediator variables are slight, implying that the data do not exhibit large fluctuations and are thus suitable for subsequent empirical testing.

5. Results

5.1. Regression analysis

Mixed regression, fixed effect, and random effect models tested model (1). The results show an F test value of 16.26, significant at the 1 % level, and a Hausman test value of 16.69, also passing the significance test. Therefore, the fixed effects model should be used for the panel data.

This paper applies the fixed effect model to test the impact of green finance on regional emission reduction, using Stata18 to regress the model. The results are shown in Table 3. Column (1) of Table 3 shows the regression results without adding control variables, from

Table 2
Descriptive statistics of variables.

Variables	Symbols	Mean Value	Standard Deviation
Sulfur dioxide intensity	LNSO2	3.169	1.398
Green Finance Index	GR	0.321	0.063
Green Credit	CREDIT	0.532	0.150
Green Securities	BOND	0.206	0.169
Green Investment	INVEST	0.022	0.007
Green Insurance	INSUR	0.663	0.272
GDP per capita	LNGDP	1.387	0.527
Technology level	LNRD	0.163	0.108
Openness Level	FDI	0.023	0.020
Government Involvement	GOV	0.438	0.257
Population Density	LNPOPU	7.858	0.432
Marketization Level	LNMAR	2.003	0.261
Advanced Industrial Structure	AIS	1.222	0.685
Green Technology Innovation	LNGTI	7.772	1.513

which it can be seen that the green finance index is significantly negative at the 1 % level, indicating that the development of green finance is beneficial to environmental protection, reduces pollution emissions, and is beneficial to the environment [25,28]. Column (2) shows the regression results obtained by adding control variables. The magnitude and significance of the effect of the green finance index on the intensity of sulfur dioxide did not undergo many changes, which indicates that this conclusion is relatively stable and supports hypothesis 1.

For the control variables, GDP per capita and technology level can significantly reduce sulfur dioxide intensity with the gradual change in China's economic development in the process of economic development while focusing on environmental protection. More excellent investment in the environment typically ensues as a region advances economically, facilitating regional emissions reduction overall. Moreover, advancements in technology can contribute to ameliorating emissions during and after the emission process. With the improvement of the technology level, the efficiency of energy use will be significantly improved, and the level of management of pollutants generated at the end of production will be improved, prompting the progress of regional emission reduction. The openness level, government involvement, population density, and marketization level all have positive impacts on sulfur dioxide intensity. The openness level is positively correlated with an increase in sulfur dioxide intensity, suggesting that foreign investors in China prioritize mitigating pollution in their own countries and transferring pollution to China. Higher government fiscal spending is directly related to higher sulfur dioxide intensity, confirming that government intervention can increase pollution. Therefore, the government should formulate policies to encourage polluting enterprises to participate in environmental management rather than increase fiscal spending. The positive impact of population density is consistent with expectations. However, the marketization level coefficient is insignificant. This is likely due to China's initial exploration stage in environmental management marketization, which has not yet formed a framework to stimulate participation by all parties or produce a systematic impact on regional emission reduction.

Since the green finance index in this paper consists of four secondary indicators, namely, green credit, green securities, green investment, and green insurance, this paper next tries to test the performance of each secondary indicator in regional emission reduction. The regression results of the fixed effect model of each secondary indicator are shown in Table 4.

Table 4, Column (1) presents the finding that green credit, measured as 1 minus the proportion of interest expenses in high energy-consuming industries, negatively correlates with sulfur dioxide intensity. This result implies that a higher level of green credit development can assist in reducing sulfur dioxide intensity levels. Green credit is the most extensive and mature aspect of China's green financial system. It has been acknowledged by scholars for its effectiveness in reducing emissions. Green credit indirectly influences high-polluting enterprises by financing constraints, resulting in reduced production, increased environmental management investments, and decreased pollution emissions [52]. Moreover, green credit helps to optimize China's industrial structure and positively impacts industrial upgrading [53].

This paper's green investment index encompasses the environmental management pollution investment ratio and energy saving and environmental protection public expenditure ratio. Following the exiting method, the same weight was assigned to subdivisions under the same level of indicators [51]. Hence, the green investment in each region is the average value of the environmental management pollution investment ratio and energy saving and environmental protection public expenditure ratio, as depicted in Column (3) of Table 4. Green investment can significantly reduce sulfur dioxide intensity and has been statistically tested at the 1 % level. As the primary participant in environmental governance, the government represents the core force of green investment. The government's extensive environmental protection investment expenditure not only brings scale benefits but also provides environmental protection signals to firms with high pollution levels, directing them to increase their R&D investments, leading to reduced pollutant emissions during and after production [54,55].

The empirical findings in Column (2) reveal that the impact of green securities on emission reduction is insignificant, suggesting

Table 3
Regression results of green finance impact on regional emission reduction.

Variables	(1)	(2)
	LNSO2	LNSO2
GR	−1.446***	−1.465***
	(0.376)	(0.373)
LNGDP		−0.607***
		(0.220)
LNRD		−4.746***
		(0.953)
FDI		2.814*
		(1.702)
GOV		0.279
		(0.195)
LNPOPU		0.0371
		(0.113)
LNMAR		0.197
		(0.247)
Constant	4.773***	5.013***
	(0.123)	(1.130)
R-squared	0.921	0.929

Note: *, **, *** represent significance at 10 %, 5 %, and 1 %.

Table 4
Emission reduction effects of secondary indicators of green finance.

Variables	(1)	(2)	(3)	(4)
	LNSO2	LNSO2	LNSO2	LNSO2
CREDIT	−1.774***			
	(0.276)			
BOND		0.440		
		(0.331)		
INVEST			−13.67***	
			(3.761)	
INSUR				0.098
				(0.069)
LNGDP	−0.656***	−0.467**	−0.567**	−0.420*
	(0.211)	(0.222)	(0.220)	(0.222)
LNRD	−4.122***	−4.790***	−4.881***	−4.972***
	(0.924)	(0.976)	(0.955)	(0.973)
FDI	3.060*	2.876*	2.679	2.813
	(1.639)	(1.740)	(1.708)	(1.738)
GOV	0.289	0.168	0.259	0.161
	(0.187)	(0.197)	(0.195)	(0.197)
LNPOPU	0.0676	0.0875	0.0332	0.0747
	(0.108)	(0.115)	(0.114)	(0.115)
LNMAR	0.284	0.280	0.203	0.253
	(0.238)	(0.254)	(0.248)	(0.252)
Constant	3.091***	4.079***	4.895***	4.048***
	(1.075)	(1.128)	(1.131)	(1.128)
R-squared	0.934	0.925	0.928	0.926

Note: *, **, *** represent significance at 10 %, 5 %, and 1 %.

that their potential for reducing emissions has not been fully realized. This could be attributed to the relatively small number of green-listed enterprises on the primary board in China, accounting for a small percentage of the total market capitalization [56]. While environmental protection issues receive more attention during the listing and financing processes, the post-listing inspection mechanism is insufficient, resulting in weak environmental protection investments by enterprises, potentially diminishing the effect of green securities on emission reduction. As for green insurance, implementing environmental liability insurance by Chinese businesses is relatively new. China's agricultural sector is most severely affected by disasters. To assess green insurance, we measured the payout rate of agricultural insurance. We found no significant impact on sulfur dioxide intensity in Column (4) of Table 4. China's agricultural sector has experienced significant reductions in size, and the proportion of GDP is declining. At the same time, our insurance industry is still in the preliminary development stage. Green insurance has put forward higher requirements for the insurance industry. Time is needed to improve green insurance itself and its function. Therefore, the role of emission reduction is not unlike that of other green products.

5.2. Heterogeneity analysis

China's eastern, central, and western regions exhibit substantial economic and ecological disparities. Moreover, each region's green finance development level is significantly distinct. To ensure the accuracy of the paper's findings, we analyze the effect of green finance on regional emission reduction separately for each region. However, as the central and western regions are often categorized based on their economic progress, the results for these two regions demonstrated a high degree of similarity. Consequently, this research combines them for analysis.

Fixed-effect model columns (1) in Table 5 reveal a negative link between the green finance index and sulfur dioxide intensity in the

Table 5
Heterogeneity analysis.

Variables	Eastern	Central and Western
	(1)	(2)
	LNSO2	LNSO2
GR	−2.747**	−0.318
	(0.745)	(0.366)
Constant	−1.534	7.090***
	(0.633)	(0.000)
Provinces	YES	YES
Year	YES	YES
R-squared	0.923	0.960
Observations	132	228

Note: *, **, *** represent significance at 10 %, 5 %, and 1 %.

eastern region, conspicuous at the 5 % level. However, the green finance index has no significant effect in other regions. These results suggest enhancing green finance in the central and western regions to achieve emission reduction goals. Overall, the findings suggest that the effect of the green finance index on regional emission reduction is more substantial in the eastern region than in the central and western regions. The reasons for this exist mainly in the following aspects:

First, the industrial structure in different regions significantly affects their respective green finance levels. Tertiary industry is prevalent in the eastern region. In contrast, secondary industry holds a larger share in the central and western regions. As a result, the high-interest expenditure and A-share market value in energy-intensive industries in the central and western regions impede progress in green finance. Second, each region exhibits unique characteristics in terms of economic development and policy priorities, which influence the allocation of green finance. With its advanced economic development, the eastern region emphasizes high-quality growth and allocates more resources to environmental protection. As the primary source of pollution emissions, regional enterprises also purchase green insurance products to effectively hedge risks. However, with a relatively weak economy, the central and western regions have many energy provinces unaware of the importance of green development, prioritizing their interests. Last, although the central and western regions are relatively backward regarding economic development, they are rich in natural resources. Foreign investors mainly consider the central and western regions' lower production costs, transferring environmental pollution to these areas and building factories there, thus worsening the environment in these regions compared to the eastern region.

Tables 6 and 7 illustrate the impact of secondary indicators of green finance on regional emission reduction in the eastern, central, and western regions. Table 6 reveals that similar to the overall regression model, green credit and green investment significantly reduce regional emissions. In contrast, the impact of green insurance on regional emission reduction is insignificant. However, green securities differ from the overall regression. Green securities increase pollutant emissions significantly, consistent with the paper [57]. Due to the immaturity of China's green securities mode, green securities mainly focus on the environmental protection verification of enterprises in the early stages. The lack of supervision by environmental protection departments of listed companies after financing leads to insufficient motivation to omit environmental protection information and to improve environmental performance. The listed companies may focus more on increasing production capacity and expanding market capitalization rather than environmental protection. As seen in Table 7, green credit and green insurance significantly impact emission reduction in the central and western regions. In contrast, green securities and green investments are not significant.

The effect of green credit in the eastern, central and western regions on pollutant emissions is significantly different. We will randomly sample 500 times to analyze between-group heterogeneity. The eastern region is set to area_1, and the central and western regions are set to area_0. The between-group heterogeneity results indicate only 22 times in the 500 samples area_0> area_1. The results showed that Fisher's permutation test passed. Therefore, it can be considered that compared with the eastern region of the development of green credit and the central and western regions of the green credit role played by green credit, there is still a significant gap.

5.3. *Influence mechanism*

Drawing on the theoretical framework established in the third section, we found that green finance has a constructive influence on reducing sulfur dioxide intensity by encouraging the adoption of an advanced industrial structure and bolstering levels of green technology innovation. Consequently, by adopting a mediating effects model, this paper assesses the mechanism behind green finance's impact on sulfur dioxide intensity. Building on the work of scholars, the ratio of the value added of the tertiary industry to that of the secondary industry serves as a measure of the advanced industrial structure [18,58]. The ratio reflects the trend of China's economic structure toward the service sector, where the service industry tends to have lower pollution emissions. Therefore, a larger ratio indicates a more evident trend of upgrading the industrial structure toward an advanced structure, resulting in lower pollution emissions.

Table 6
Sub-sample regression of secondary indicators of green finance: eastern region.

Variables	(1)	(2)	(3)	(4)
	LNSO2	LNSO2	LNSO2	LNSO2
CREDIT	−3.198***			
	(0.485)			
BOND		3.286***		
		(0.950)		
INVEST			−21.59***	
			(7.905)	
INSUR				−0.115
				(0.248)
Constant	−1.347	−4.961	−2.714	10.43***
	(2.842)	(3.231)	(3.262)	(1.555)
Controls	YES	YES	YES	YES
R-squared	0.939	0.922	0.919	0.739
Observations	132	132	132	132

Note: *, **, *** represent significance at 10 %, 5 %, and 1 %.

Table 7
Sub-sample regression of secondary indicators of green finance: central and western region.

Variables	(1)	(2)	(3)	(4)
	LNSO2	LNSO2	LNSO2	LNSO2
CREDIT	−0.550**			
	(0.276)			
BOND		0.078		
		(0.270)		
INVEST			−3.357	
			(3.794)	
INSUR				−0.226**
				(0.107)
Constant	6.429***	6.947***	7.083***	10.43***
	(0.926)	(0.897)	(0.907)	(1.555)
Controls	YES	YES	YES	YES
R-squared	0.960	0.960	0.960	0.833
Observations	228	228	228	228

Note: *, **, *** represent significance at 10 %, 5 %, and 1 %.

Green technology innovation is another mechanism for assessing the relationship between green finance and regional emission reduction. Consistent with the approach taken by scholars, this paper utilizes the total number of green invention patents and green utility model patents in each province as the green technology innovation indicator, adding one to the count and then taking the natural logarithm [46]. A higher score reflects more significant green technology innovation within the province.

Table 8 column (1) exhibits a positive association between green finance and industrial structure advancement at the 1 % significance level, implying green finance's significant ability to promote an advanced industrial structure. Column (2) of the regression outcomes indicates that both green finance and the mediator variable of the advanced industrial structure are negatively related to sulfur dioxide intensity. This suggests that the development of green finance and advanced industrial structure simultaneously reduces sulfur dioxide intensity, and the advanced industrial structure mediates the decrease in sulfur dioxide. As the tertiary industry's added value significantly surpasses the secondary industry, China's industrial structure is shifting toward a greener and more rational direction. Furthermore, it further supports this paper's second hypothesis that an advanced industrial structure mediates green finance and sulfur dioxide intensity. To thrive in the long term, China needs to modify and develop its original model toward greener and more eco-friendly areas to replace the outdated development model.

Columns (3) and (4) assess the impact of green technology innovation on reducing sulfur dioxide intensity. In Column (3), green finance shows a significant relationship at the 1 % significance level, implying that green finance development encourages green technology innovation. Furthermore, the faster the advancement of green finance, the higher the demand for high technology. It leads to technological improvements and reduced emissions during production, thereby aiding the environment. Column (4) adds green finance and technology innovation to gauge their joint effects on sulfur dioxide intensity. The results suggest that the green technology innovation serves as a partial mediator. The analysis confirms that green finance affects sulfur dioxide intensity by enhancing the advanced industrial structure and green technology innovation. Both methods were found to be significant, thus verifying the validity of this paper's second and third hypotheses.

5.4. Robustness test

Model robustness is tested by replacing the dependent variables and excluding the interference of policy factors.

Table 8
Mediating effects.

Variables	Advanced Industrial Structure		Green Technology Innovation	
	(1)	(2)	(3)	(4)
	AIS	LNSO2	LNGTI	LNSO2
GR	1.072***	−0.697***	2.986***	−1.746***
	(0.166)	(0.368)	(1.044)	(0.590)
AIS		−0.913***		
		(0.137)		
LNGTI				−0.749***
				(0.116)
Constant	0.677***	8.7176***	6.812***	10.82***
	(0.054)	(1.196)	(0.339)	(1.620)
Controls	NO	YES	NO	YES

Note: *, **, *** represent significance at 10 %, 5 %, and 1 %.

5.4.1. Replace the dependent variable

To enhance persuasiveness in the impact of green finance on regional emission reduction and broaden the emission reduction index, we introduce a replacement dependent variable, namely, carbon dioxide intensity. This index signifies the carbon dioxide generated per unit of economic output, making it a critical measure of carbon emissions, especially in developing countries. Due to the unavailability of official CO2 emission data, this paper proposes calculating the CO2 intensity in each region using the end consumption of various fossil fuels detailed in the China Energy Statistical Yearbook and breaking down the energy into categories based on the IPCC's energy breakdown scheme. The following formula represents the calculation system:

$$CO2_j = \frac{\sum_{i=1}^{9} E_{ij} \times f_i \times Ci}{GDP_j} \tag{4}$$

where i and j represent different energy types and regions, respectively, and E_{ij} denotes energy consumption. The energy types include coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, LPG, and natural gas in a total of 9 categories. f_i denotes the standard coal conversion factor of an energy source, and C_i denotes the CO2 emission factor of an energy source.

After conducting a re-regression analysis, Table 9 reflects fresh data. In Column (1), green finance is still negatively correlated with carbon dioxide intensity, which is consistent with the conclusions of the previous regression results, indicating that the results are still robust.

5.4.2. The interference of policy factors is excluded

To prevent the impact of policy factors, the State Council stipulated five pilot provinces and regions, namely, Zhejiang, Guangdong, Guizhou, Jiangxi, and Xinjiang, to carry out green finance operations in June 2017. The data from these five regions were removed before regression analysis to eliminate this interference. The results are presented in Column (2) of Table 9, where the green finance index demonstrates statistical significance levels of 1 %, indicating the robustness of the basic regression results.

Table 10 shows the regression results of green finance secondary indicators on the dependent variable - carbon dioxide intensity, and Table 11 shows the results of the robustness test of green finance secondary indicators excluding the green finance pilot in Zhejiang, Guangdong, Guizhou, Jiangxi, and Xinjiang provinces. From the two tables, we can see that green credit and green investment are still significant. In contrast, the green securities and green insurance results are insignificant, consistent with the previous findings. The robustness test shows that green credit and green investment have a more noticeable effect on pollution reduction among green financial instruments.

Through empirical tests, this paper concludes that green finance can significantly reduce the intensity of sulfur dioxide. That is, green finance has a significant positive impact on regional pollutant emission reduction. This finding is consistent with the conclusions made by the scholars [16,31]. In exploring the effect of green financial instruments on regional emission reduction, the scholar discovered that green credit and green venture capital had notable emission reduction effects [21]. However, the coefficient of green venture capital bore no significance when both variables were present in the same model.

Similarly, scholars have empirically found that green credit, green industry investment, and green bonds all reduce regional carbon emissions. However, the coefficient of green bonds was no longer significant, indicating an absence of emission reduction effects [59]. Similarly, this paper affirms that green credit shows a robust emission reduction effect. At the same time, green investment also

Table 9
Robustness test results.

Variables	(1)	(2)
	LNCO2	LNSO2
GR	−0.451***	−1.909***
	(0.131)	(0.413)
LNGDP	−0.863***	−0.550**
	(0.0772)	(0.251)
LNRD	−1.510***	−4.347***
	(0.334)	(1.033)
FDI	0.321	2.294
	(0.596)	(1.787)
GOV	0.131*	0.222
	(0.0684)	(0.234)
LNPOPU	0.0528	0.172
	(0.0396)	(0.131)
LNMAR	0.179**	0.144
	(0.0867)	(0.291)
Constant	1.359***	4.152***
	(0.396)	(1.283)
R-squared	0.879	0.928
Number of Provinces	30	25
Observations	360	300

Note: *, **, *** represent significance at 10 %, 5 %, and 1 %.

Table 10
Robustness tests for replacing the dependent variables.

Variables	(1)	(2)	(3)	(4)
	LNCO2	LNCO2	LNCO2	LNCO2
CREDIT	−0.479***			
	(0.0988)			
BOND		0.045		
		(0.116)		
INVEST			−3.819***	
			(1.321)	
INSUR				−0.0264
				(0.0234)
Constant	0.804**	1.070***	1.299***	1.347***
	(0.384)	(0.394)	(0.397)	(0.375)
Controls	YES	YES	YES	YES
R-squared	0.883	0.874	0.877	0.849

Note: *, **, *** represent significance at 10 %, 5 %, and 1 %.

Table 11
Robustness tests excluding interference from policy factors.

Variables	(1)	(2)	(3)	(4)
	LNSO2	LNSO2	LNSO2	LNSO2
CREDIT	−2.489***			
	(0.319)			
BOND		0.395		
		(0.360)		
INVEST			−16.67***	
			(4.224)	
INSUR				−0.184
				(0.123)
Constant	2.105*	2.804**	3.874***	8.533***
	(1.175)	(1.301)	(1.291)	(2.012)
Controls	YES	YES	YES	YES
R-squared	0.937	0.922	0.926	0.755
Number of Provinces	25	25	25	25
Observations	300	300	300	300

Note: *, **, *** represent significance at 10 %, 5 %, and 1 %.

demonstrates a significant impact. However, the emission reduction effects of green securities and green insurance remain unexplored.

One potential reason for the lack of significant emission reduction effects of green securities and green insurance may be the historical development model prioritizing polluting enterprises, with heavily polluting entities holding a more substantial market value than their environmentally friendly counterparts. Changing this weighted structure would require significant time. Furthermore, the decreasing scale and share of agriculture in China's GDP and the nascent stage of its insurance industry with many limitations further contribute to the lack of notable emission reduction effects for these two aspects of green finance. This paper explores the mechanisms underlying how green finace affects regional emission reduction. This confirms that an advanced industrial structure and green technology innovation play a crucial mediating role. This finding corresponds with the conclusions [58]. The heterogeneity analysis illustrates that higher levels of green finance in the eastern regions have a more potent inhibitory effect on regional emission reduction than in the central and western regions.

5.4.3. Endogenous analysis

Although this paper adds control variables and factors that vary with individuals and time, there are still problems, such as omitted variables, and endogeneity caused by these problems may bias the estimation results; Therefore, this paper chooses the instrumental variable method to address the endogeneity problem. This paper chooses the green finance index lagged by one period as an instrumental variable [60]. Instrumental variables must fulfill the two conditions of correlation and exogeneity: (1) High correlation. There is a certain degree of continuity in developing the green finance index. The current green finance index is primarily influenced by the green finance index of the previous period, so it can be considered that there is a high degree of correlation between the two variables. (2) Strict exogeneity. Since the pollution emission intensity in the current period is unlikely to affect the green finance development index in the previous period, the green finance index together afterward satisfies exogeneity. The results of the 2SLS estimation using the green finance index in the lagged period are shown in Table 12. Column (1) reports the effect of the green finance index in the lagged period as an instrumental variable on the green finance index in the current period, and the result shows that there is a positive effect between the two at the 1 % significance level, which is 0.27, and Column (2) reports the effect of the green finance index on the intensity of sulfur dioxide when the instrumental variable is selected. The results are negative at the 1 % significance level,

consistent with the results of the basic regression.

To test the validity of the instrumental variables, this paper performs under-recognition and weak instrumental variable tests. The results show that the p value of the LM test is 0.00, and there is no under-recognition problem. In addition, the Cragg-Doald Wald F statistic value is 20.88, which is significantly greater than 16.38, rejecting the hypothesis of a weak instrumental variable problem. Therefore, choosing the green finance index with a one-period lag as the corresponding instrumental variable is reasonable and adequate.

6. Conclusions and policy recommendations

6.1. Conclusions

First, Green finance negatively influenced sulfur dioxide intensity in both models. Green credit and green investment demonstrated more substantial emission reduction effects among the secondary indicators of green finance. In contrast, green securities and green insurance have not yet contributed to emission reduction. Second, green finance positively influences pollution emission reduction through advanced industrial structures and green technology innovation. Additionally, green finance's particular capital rationing function supports new environmental protection industries while imposing financing restrictions for heavily polluting industries, ultimately contributing to their transformation and upgrade.

Moreover, green finance promotes the improvement of green technology innovation levels. It increases energy utilization efficiency while reducing the emission of pollutants during production, resulting in improved regional emission reduction effects. Third, according to the heterogeneity analysis, the eastern region has a considerably higher standard of development in green finance and an increased emission reduction impact than the other regions. Green credit and green investment have contributed significantly to emission reduction in the eastern region. In contrast, green securities have resulted in increased pollution emissions. Conversely, green credit and green insurance are central and western regions' primary emission reduction methods.

6.2. Policy recommendations

According to the research conclusion of this paper, the following four policy suggestions are proposed.

(1) Promotion of the development of green finance. Green credit has the most significant emission reduction effect. It is necessary to provide preferential loans to environmentally friendly enterprises and pay more attention to the environmental technology upgrade of high-pollution enterprises. Encourage capable high-pollution enterprises to undergo technological transformation. The emission reduction effect of green securities is not significant. Therefore, regulatory authorities should strengthen the supervision of listed companies and conduct regular inspections through multiple channels. In terms of green investment, implement the principle of "polluter goverance" as stated in the Environmental Protection Law, and hold companies accountable for their environmental responsibilities. In green insurance, regulatory authorities can increase innovation in insurance products and design green insurance products based on the needs of enterprises and environmental protection. Financial institutions should enhance the innovation and coverage of green financial products, establish a comprehensive information disclosure system, and achieve visualized and quantifiable effects of green finance development.

(2) Promote industrial transformation and upgrading. First, provide assistance and support for technological upgrades and the transformation of polluting enterprises. Implement mandatory elimination measures for outdated production capacity to optimize production capacity. Second, industry consolidation should be promoted through mergers and acquisitions to reduce costs and various production factors. It can also establish precise support mechanisms and facilitate the injection of funds, technology, and talent from advanced enterprises to update old production capacity, thereby unlocking significant potential.

(3) Increase investment in green technology innovation. Green technology innovation is a critical aspect of reducing pollution emissions. Green financial products and services should strengthen support for green technology innovation. The financial institutions should strengthen post-loan supervision and direct funds to research and development departments, supporting the development of new technologies and products, improving production processes, and reducing the use of raw materials and emissions of pollutants during production. Government departments should conduct regular inspections on the use of funds, project progress and environmental benefits. They should prevent research and development funds from improving production processes from being invested in inefficient production, and ensure green funds are used properly.

(4) Implement differentiated development in different regions. The empirical results show that the development effect of green finance in the eastern region is better than that in the central and western regions. Therefore, while accelerating its development, the eastern region should provide reference opinions for the central and western regions. The development of green finance in the central and western regions is slow. It requires government policies that tilt toward green finance, such as providing more favorable loan interest rates, strengthening the development of green technology and talent, and focusing on technology innovation to reduce pollutant emissions during production.

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Table 12
Instrumental variable regression.

Variables	(1)	(2)
	GR	LNSO2
L.GR	0.270***	
	(0.059)	
GR		−8.187***
		(2.740)
LNGDP	−0.015	−2.386***
	(0.014)	(0.171)
LNRD	0.017	−4.193**
	(0.1499)	(1.882)
FDI	−0.252	13.398***
	(0.255)	(3.206)
GOV	0.063**	0.569
	(0.030)	(0.409)
LNPOPU	−0.006	−0.244
	(0.018)	(0.225)
LNMAR	0.010	−1.019**
	(0.035)	(0.433)

Note: *, **, *** represent significance at 10 %, 5 %, and 1 %.

Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Leiling Wang: Writing – original draft, Conceptualization. **Xiaoyun Yang:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Qihua Cai:** Writing – review & editing, Validation, Software, Project administration.

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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