



Green finance and the synergistic effects of pollution and carbon emission reduction: evidence from China

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Abstract

This paper examines the spatial-temporal evolution of green finance development (GFD) and the synergistic effects of pollution and carbon emission reduction (SEPCR) in China, using data from 2008 to 2022. It elucidates: (1) GFD in China is progressively improving, showing a regional disparity pattern of “eastern region > central region > western region”. The SEPCR index initially increases and then decreases, displaying a regional disparity pattern of “central region > eastern region > western region”, with the gap between the eastern and western regions narrowing and the gap between the eastern and central regions widening. (2) GFD can enhance SEPCR; however, as the level of GFD intensifies, its impact diminishes, demonstrating nonlinear characteristics. (3) The impact of GFD on SEPCR is more prominent in regions with high levels of financial development, high levels of information technology development, and high environmental governance intensity.

Keywords Green finance · Synergistic effects · Spatial-temporal patterns · Influence mechanism · Threshold effects

1 Introduction

Since 1978, China’s economy has undergone rapid development. However, this swift growth has also led to a series of resource and environmental challenges, including escalating resource consumption, increased greenhouse gas emissions, and deteriorating ecological conditions, all of which directly impact people’s well-being. In 2006, China’s total carbon emissions topped the global list. The impact of air pollution on public health in China

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was severe in 2012. According to the “China’s Ecological Environmental Statistics Annual Report for 2023,” the average temperature in China in 2023 was the highest since 1951, with 31% of cities exceeding PM 2.5 standards and 23.3% exceeding ozone standards. Some cities have repeatedly faced environmental pollution issues. Since 2012, China’s resource and environmental issues have significantly improved; nonetheless, the challenges of environmental pollution and CO₂ emissions persist. Environmental pollutants and CO₂ emissions share common origins. Promoting coordinated governance has become essential for the development of China’s economy. In 2022, China issued the “Implementation Plan for Synergistic Effects Pollution and Carbon Emission Reduction (SEPCR),” which for the first time elevated coordinated control to a strategic level and provided clear guidance for these efforts. In 2024, China emphasized the need to jointly promote carbon emission reduction, pollution reduction, green expansion and growth, and actively and steadily promote the realization of the dual carbon target. Against this backdrop, how to efficiently promote the SEPCR has become a practical problem urgently needing resolution in the green transformation of China’s economy.

In October 2024, China issued the “Opinions on Leveraging Green Finance Development (GFD) in Serving the Construction of a Beautiful China.” The document proposed bolstering robust financial support and policy guarantees for GFD. As an innovative financial tool that harmonizes economic benefits with environmental benefits, GFD has garnered widespread attention from scholars both domestically and internationally. Early studies primarily focused on the qualitative analysis of the concept of GF and the rationale behind its necessity (Zhu et al., 2022), and attempted to measure its development level using relevant expressions from financial institutions or governments (Yu et al., 2017), proxy indicators related to regional markets and policy implementation evaluations (Lv et al., 2021), as well as green credit (Flammer et al., 2021) and green funds (Ma et al., 2023), among others. In recent years, with the continuous improvement of China’s GFD, research on the economic effects of GFD has intensified. Existing research indicates that GFD can enhance the quality of economic growth (Ouyang et al., 2023), promote the upgrading of regional industrial structures (Zhang et al., 2023), reduce corporate financing costs (Zhang et al., 2023), and lower energy consumption intensity (Su et al., 2022). Meanwhile, research on green finance and sustainable development has gradually become a hot topic among scholars both domestically and internationally (Jaishree et al., 2025). Studies have shown that GD can help promote the sustainable development of manufacturing enterprises (Pasupuleti et al., 2025), generate positive environmental benefits, and achieve environmental sustainability (Dhayal et al., 2023). Additionally, some studies, based on perspectives such as urban policy pilots, investor preferences, and green technology innovation, have demonstrated the significant carbon emission reduction effects of GFD (Pang et al., 2022). Other studies have also pointed out that GFD can enhance corporate pollution control capabilities through policy transmission, financing constraints, and capital diversion (Zhang et al., 2024; Lan et al., 2023).

The existing research provides valuable insights for analyzing the impact of GFD on the SEPCR, yet it is not without its limitations. On one hand, studies on the environmental impact of GFD often concentrate on CO₂ emissions or specific aspects of pollutant emissions (Wang et al., 2025), and research into reducing pollution emissions and carbon emissions tends to be addressed separately (Hu et al., 2023). Few studies have provided a comprehensive evaluation of the SEPCR, and even fewer have analyzed the transmission mechanisms

and impact of GFD on SEPCR. Additionally, most studies on pollution emission reduction focus solely on the reduction of individual pollutants, predominantly air pollutants such as SO₂, NO_x, or PM_{2.5} (Fan et al., 2024; Yuan et al., 2023). Few studies have considered pollution reduction from the perspective of solid waste, exhaust gas, and wastewater, collectively known as the “three wastes”. On the other hand, in studies on the SEPCR, the majority of literature concentrates on representative green financial derivatives like green credit, green bonds, etc. (Garcia et al., 2023). Few studies employ a comprehensive indicator system to measure the GFD and conduct empirical research based on this, potentially leading to inaccurate conclusions about the impact of GFD on the SEPCR.

Consequently, this paper, from the perspective of synergistic governance, initially constructs a synergy index for pollution and carbon emission reduction that includes a “three wastes” pollution index and CO₂ emissions, as well as a GFD index. It then analyzes their spatial-temporal pattern evolution and regional differences. Secondly, the double fixed effect model and threshold effect model were used to study the nonlinear effect of GFD on the SEPCR and its mechanism, aiming to provide reference suggestions for the green transformation of economic development. The structure of this paper is as follows: The second part is theoretical analysis and hypotheses. The third part outlines the research design, models, variables, and data sources. The fourth part presents the results, including the spatial-temporal pattern evolution of GFD and SEPCR, as well as empirical results. The fifth part concludes with conclusions and discussions.

2 Theoretical analysis and hypothesis

2.1 The impact of GFD on the SEPCR

Based on the innovation system theory and green growth paradigms, this paper examines the influence mechanism of GFD on the SEPCR across three dimensions: source prevention, process control, and end-of-pipe treatment (Fig. 1). In the source prevention phase, GFD

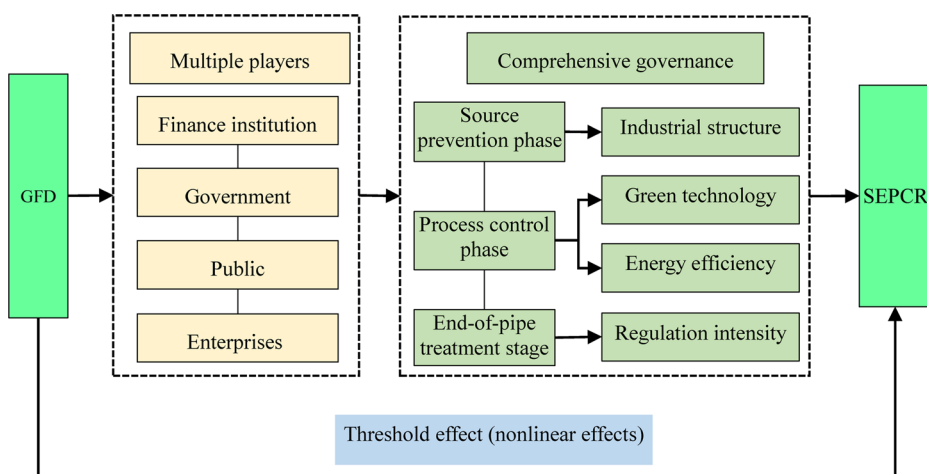


Fig. 1 The influence mechanism of GFD on the SEPCR

can strengthen the SEPCR by facilitating the upgrading of industrial structures based on transition management theory. On one hand, by leveraging innovative financial products, GFD can channel funds into green industries (Liu et al., 2024a, b), which can increase the overall utilization of clean energy, refine the energy consumption structure, and shift away from the traditional fossil fuel-based consumption model. This provides favorable financial support for the growth and expansion of green industries. Simultaneously, GFD exerts a crowding-out effect on “high-pollution, high-energy consumption, and overcapacity” industries by tightening financing constraints, increasing financing costs, and enforcing environmental information disclosure (Wang & Wang, 2021), thereby inhibiting their expansion and compelling a transition towards greener and low-carbon practices, thus enhancing the SEPCR. On the other hand, the ongoing evolution of GFD can also heighten public awareness of energy conservation and environmental protection, subsequently guiding consumers towards green consumption. To align with consumer preferences for greener options and maximize profits, enterprises will boost investment in green industries. Moreover, enterprises that have already invested in green initiatives will generate positive spillover effects (Wu et al., 2022) within their industry, fostering the green transformation of industrial structures and further enhancing the SEPCR.

During the process control phase, GFD enhances the SEPCR by promoting green technological innovation and improving energy utilization efficiency (Wang et al., 2021). With respect to green technological innovation, it cannot be divorced from financial support. Green technological innovation is characterized by lengthy R&D cycles, substantial investment costs, and uncertain outcomes, which impose significant investment risks on innovators. On one hand, GFD attracts more investors to invest in high-risk, high-reward green and low-carbon industries through a range of green financial products with varying maturities, liquidity, and preferential schemes. This reduces the financial flow risks associated with green technological innovation, thereby boosting companies’ enthusiasm for green and low-carbon production. Additionally, to adapt to the GFD, some companies may innovate their existing technologies or directly adopt new green technologies. On the other hand, environmental regulations spurred by GFD will compel companies to innovate green technology and provide certain financial support. In terms of energy efficiency, GFD sends positive signals about green, low-carbon, and efficient production to enterprises through differentiated loan interest rates and loan term combinations, encouraging them to innovate production equipment and processes, thereby improving energy efficiency. Furthermore, GFD utilizes its resource allocation function to crowd out high-pollution, high-emission, and low-efficiency traditional manufacturing enterprises, offering survival space and financial support for green and efficient manufacturing enterprises, thus enhancing overall industrial energy efficiency.

At the end-of-pipe treatment stage, GFD can enhance environmental regulation and improve the SEPCR. Environmental regulations reflect the degree to which the government emphasizes ecological conservation. GFD has received strong support from the state, prompting the local governments to pay close attention to economic development while giving high priority to environmental protection. The continuous improvement of relevant environmental protection systems, tax incentive mechanisms, and supervision and management frameworks can promote the SEPCR to a certain extent. Meanwhile, as green financial products continue to innovate and develop, more and more investors recognize the importance of ecological conservation. In addition, with the growing environmental awareness

of the government and the public, their requirements for environmental quality have also increased. The government and the public will become more proactive in participating in environmental governance and supervision, which can also enhance the SEPCR to some extent.

Accordingly, this paper proposes the following research hypotheses:

Hypothesis 1 *GFD can enhance the SEPCR.*

Hypothesis 2 *GFD can enhance the SEPCR through four avenues: upgrading the industrial structure, innovating green technology, improving energy efficiency, and strengthening environmental regulation.*

2.2 Threshold effect of GFD on the SEPCR

The impact of GFD on the SEPCR may exhibit a nonlinear threshold effect with diminishing marginal influence. GFD can lead to differences in its impact on the SEPCR. In the early stages of GFD, strong national support, high government attention, and continuous improvement of the financial system, along with sustained public participation, have directed resources towards green industries. This has been beneficial for enhancing the SEPCR. However, due to various factors such as limited resource allocation, insufficient supply of professional talents, bottlenecks in green technological innovation, and overly stringent environmental regulations, the impact of a high level of GFD on the SEPCR will diminish. Moreover, the high investment required by GFD for green and low-carbon industries also means high costs for the synergistic governance. These costs can directly affect enterprises' investment enthusiasm and the progress of project development, and may even lead some enterprises to take risks and engage in "greenwashing" or "fake green" practices (Flammer et al., 2021), thereby reducing the impact of GFD on SEPCR.

Thus, hypothesis 3 is proposed: The impact of GFD on the SEPCR has a threshold effect.

3 Method

3.1 Model

3.1.1 Benchmark model

Based on the results of the Hausman test, where the H statistic is significant, the fixed effects model is chosen. Additionally, taking into account individual and time effects, the double fixed effects model is ultimately selected. To assess the impact of GFD on SEPCR, the model is formulated as follows:

$$twi_{it} = \alpha_0 + \alpha_1 gfi_{it} + \alpha_2 X_{it} + \mu_i + v_t + \epsilon_{it} \quad (1)$$

Among them, twi_{it} refer to the SEPCR for i province in the t year, gfi_{it} is the GFD for i provinces in the t year, X_{it} are the control variables, μ_i and v_t represent the fixed effects

of province and time, ϵ_{it} is the disturbance term, α_0 is the constant term, α_1 and α_2 are the estimated parameters.

Due to the inherent flaws in the traditional three-step method, and the regression results may be inaccurate. To more effectively test the mechanism through which GFD affects SEPCR, this paper adopts the research approach of Jiang (2022) and directly examines the impact of GFD on the mechanism variables. The specific model is as follows:

$$Mev_{it} = \beta_0 + \beta_1 gfi_{it} + \beta_2 X_{it} + \mu_i + v_t + \epsilon_{it} \quad (2)$$

Among them, Mev_{it} is the mechanism variable; β_0 represents the constant term, β_1 and β_2 represent the estimated parameters; other variables and symbols remain same as those in the previous section.

3.1.2 Threshold model

To further investigate the threshold effect of GFD on the SEPCR, this paper establishes a threshold model with GFD as the threshold variable:

$$twi_{it} = \theta_0 + \theta_1 gfi * I(threshold_{it} \leq \gamma) + \theta_2 gfi * I(threshold_{it} > \gamma) \\ + \theta_n X_{it} + v_t + \epsilon_{it} \quad (3)$$

In the formula, θ_0 represents the constant term, θ_1 and θ_2 represent the estimated parameter, $threshold_{it}$ is the value of GFD in the t province, and γ represents the specific threshold value; $I(\cdot)$ evaluates to 1 when the corresponding condition is true, otherwise it is 0; other variables and symbols are the same as those in the previous section.

3.1.3 Entropy model

Green finance measurement necessitates not only the quantification of individual indicators but also the assignment of appropriate weights to construct a composite index. There are two methods for weight assignment: subjective weighting and objective weighting. Subjective weighting method assigns corresponding weights based on the relative importance of each indicator, with primary approaches including expert scoring, principal component analysis, Delphi, and AHP. However, this method is susceptible to human subjective factors and cannot objectively reflect the level of GFD. Objective weighting method assigns corresponding weights based on the original data of indicators, with primary approaches including entropy value method, range method, and cluster analysis, which can more objectively reflect the level of GFD. This study adopts the entropy value method from objective weighting as a measurement approach for China's GFD level, according to the research methodology of Qiao et al. (2021) to minimize interference from subjective human factors. The measurement methods are as follows:

Step 1: Standardization of indicators. Given the significant differences in dimensions and orders of magnitude among GF indicators, it is necessary to standardize the original data before conducting horizontal comparisons. The standardization formulas are as follows:

Positive indicator standardization formula:

$$Z_{ij} = \frac{X_{ij} - \min X_{ij}}{\max X_{ij} - \min X_{ij}} \quad (4)$$

Negative indicator standardization formula:

$$Z_{ij} = \frac{\max X_{ij} - X_{ij}}{\max X_{ij} - \min X_{ij}} \quad (5)$$

Among them, i and j respectively represent the index of i year in j province, X_{ij} is the raw data of the index of i year in j province, $\min X_{ij}$ is the minimum value of in all years, $\max X_{ij}$ is the maximum value of in all years, and Z_{ij} is the result of standardization.

Second step: calculate the proportion d_{ij} , information entropy e_j and index weight ϕ_j of the i year in the j province. The calculation formula is as follows:

$$d_{ij} = Z_{ij} / \sum_{i=1}^m Z_{ij} \quad (6)$$

$$e_j = (-1/\ln m) \sum_{i=1}^m d_{ij} \ln d_{ij} \quad (7)$$

$$\phi_j = -(1 - e_j) / \sum_{j=1}^n (1 - e_j) \quad (8)$$

Among them, m is the number of year, n is the number of province.

Third step: calculate the value of GFDI. According to standardized indicators Z_{ij} and weights ϕ_j , the weighted multiple linear function is used to calculate the value of GFDI. The calculation formula is as follows:

$$\text{GFDI}_i = \sum_{j=1}^n \phi_j \times d_{ij} \quad (9)$$

GFDI_i represents the GFDI in a province in i year. The value ranges from 0 to 1. The higher the value is, the higher the level of GFD is.

3.2 Variable

3.2.1 Dependent variable

SEPCR is the dependent variable. Utilizing the research methodology of Lu et al. (2022), the interaction term between the environmental pollution index and total CO_2 emissions is taken as the logarithm to measure the SEPCR. This indicator is an inverse measure; the larger its value, the worse the SEPCR. Initially, same as the research approach of Deng et al. (2022), a comprehensive environmental pollution index encompassing the “three wastes” in each province from 2008 to 2022 is constructed. This is based on the total discharge of SO_2 , solid waste, and wastewater emissions. The entropy method is used to objectively weight each index, thereby calculating the index that measures the degree of environmental pollution in each province. Subsequently, using the IPCC’s carbon emission inventory, the

total CO₂ emissions from 2008 to 2022 in each province are computed with the following formula:

$$CO_2 = \sum f c_i \times scc_i \times cec_i \times 44/12 \quad (10)$$

Among them, i represents the type of carbon-containing fossil fuel ($i=1, 2, \dots, 8$ respectively denote the 8 types of energy selected for study, namely coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, and natural gas), $f c_i$ is the consumption of fossil fuels, scc_i and cec_i respectively represent the standard coal conversion factor and carbon emission factor (See Table 1), $44/12$ representing the ratio of CO₂ to the molecular weight of carbon.

3.2.2 Explanatory variables

Green finance development index (GFDI) is the core explanatory variable. Drawing upon the research methodology of Huang et al. (2022), this paper has chosen seven indicators for measurement, which include green credit, green investment, and green bonds (refer to Table 2). The entropy method is used to assign values to each indicator, and ultimately, the GFDI is calculated.

3.2.3 Mechanism variables

This paper aims to examine the entire process of environmental governance from the “source-process-end” perspectives, selecting four major variables: industrial structure upgrading (ISU), green technology innovation (GTI), energy utilization efficiency (EUE), and the intensity of environmental regulation (IER), to reveal the mechanisms by which GFD contributes to the SEPCR. Drawing on existing literature (Wang et al., 2021), ISU is measured by the ratio of the added value of the tertiary industry to the added value of secondary industry. Referring to the research by Zhang et al. (2024), GTI is assessed using four indicators: the number of green invention patent applications and grants, the number of green utility model patent applications and grants, through the entropy method for objective valuation. EUE is measured by the ratio of regional GDP to total energy consumption. IER is indicated by the proportion of energy conservation and environmental protection expenditures in local fiscal spending out of total fiscal expenditure.

Table 1 Carbon emission calculation parameters for various fossil energy source (Bi et al., 2023)

Energy type	Standard coal conversion coefficient (104tce/104t)	Carbon emission conversion factor (104t/104tce)
Raw coal	0.7143	0.7559
Coke	0.9714	0.8550
Crude oil	1.4286	0.5857
Gasoline	1.4714	0.5530
Kerosene	1.4714	0.5714
Diesel oil	1.4571	0.5921
Gas	1.4286	0.6185
Natural gas	13.3000	0.4483

Table 2 Indicators and measurement methods

Index	Description		Indicator attributes
SEPCR	Pollution Emissions	Total emissions of SO ₂ , solid waste and water waste	-
	CO ₂ Emissions	Total emissions of CO ₂ from energy consumption	-
GFDI	Green credit	Credit for environmental protection projects/total credit	+
	Green investment	Investment in environmental pollution control as a share of GDP	+
	Green insurance	Environmental pollution liability insurance income/total premium income	+
	Green bonds	Total green bond issuance/total bond issuance	+
	Green support	Proportion of expenditure on fiscal and environmental protection	+
	Green fund	Total market value of green funds/total market value of all funds	+
	Green rights	Total amount of carbon trading, energy use right trading and emission right trading/rights market trading	+

3.2.4 Control variables

This paper employs methodologies from contemporary research to identify control variables from two primary domains: meteorological factors and economic factors. The selected control variables are as follows. Annual average precipitation is considered due to its close relationship with air pollution and its significant influence on CO₂ and pollutant dispersion (Li et al., 2022). Economic development is recognized as a crucial factor affecting CO₂ and pollutant emissions, measured by per capita GDP. External openness is another factor that can both promote and suppress CO₂ and pollutant emissions (Dauda et al., 2021), and thus it is essential to include this in our considerations. This paper utilizes the ratio of local import and export volume to regional GDP as a measure. The government's fiscal capacity has direct and indirect effects on CO₂ and pollutant emissions (Halkos et al., 2013). When fiscal capacity is sufficient, governments tend to prioritize green and low-carbon development. Additionally, enhanced fiscal capacity can stimulate economic growth, boost energy consumption, and subsequently increase CO₂ and pollutant emissions. Government fiscal capacity is measured by the ratio of general budget expenditure to regional GDP. Human capital may have a non-linear impact on CO₂ and pollutant emissions (Huang et al., 2021). As human capital levels rise, emissions may be reduced through green technological innovation, optimization of industrial structure, and increased awareness of environmental regulations. Conversely, emissions could increase due to economic development and higher energy consumption. This paper characterizes human capital by the ratio of the number of students enrolled in higher education to the total population. Transportation infrastructure enhances inter-regional accessibility, increases traffic flow and economic activity interaction, thereby elevating energy and resource consumption and regional carbon dioxide and pollutant emissions (Wang et al., 2024). This paper uses the logarithm of highway mile-

age to represent transportation infrastructure. Industrial progress often involves substantial energy and resource consumption (Liu et al., 2018), and the industrial production process is a major source of CO₂ and pollutant emissions. It is a key factor that cannot be overlooked. In this paper, the ratio of industrial added value to regional GDP is used to represent industrial progress.

3.3 Data and descriptive statistics

The panel data from 30 provinces in China, spanning from 2008 to 2022, have been selected. Due to significant data gaps and inconsistent statistical criteria, samples from Tibet, Hong Kong, Macao, and Taiwan have been omitted. All data utilized in this study are from the China Statistical Yearbook, EPS database, China Climate Bureau, and provincial statistical yearbooks. To ensure data integrity, some missing values have been filled using interpolation methods. The results of the statistical analysis for each variable are presented in Table 3.

4 Result

4.1 Spatial-temporal pattern analysis

4.1.1 Analysis of the spatial-temporal pattern of GFDI in China

The results depicted in Fig. 2 indicate that China's GFDI is experiencing a gradual upward trend. At the national level, the GFDI increased from 0.249 in 2008 to 0.374 in 2022, with an

Table 3 Descriptive statistics

Variable type	Variables	Variable definition	Mean	S.E
Dependent variable	SEPCR	SEPCR	8.729	1.430
Explanatory variables	GFDI	GFDI	0.312	0.122
Controlled variable	Transportation Facilities (jtss)	The logarithm of the road mileage	11.662	0.857
	Fiscal capacity (cznl)	Fiscal budget expenditure/GDP	0.251	0.109
	Average annual precipitation (pjjs)	The logarithm of average annual precipitation	6.693	0.649
	Economic development (pgdp)	The reciprocal of GDP per capita	10.718	0.551
	Human capital (sjyl)	Number of students in colleges and universities/total population	0.02	0.008
	Industrial Development (gysp)	Industrial added value/GDP	0.345	0.084
	Openness to the outside world (opcd)	Total import and export volume/GDP	0.284	0.307

average annual growth rate of 2.9%, suggesting that it is continuously rising. At the regional level, the GFDI across all regions exhibits a gradual upward trend with significant spatial differentiation, presenting a distribution pattern where the eastern region (0.389) > central region (0.298) > western region (0.245). And over time, the differences in GFDI among regions have been increasing. From 2008 to 2022, the eastern region increased by 0.155, the central region by 0.121, while the western region only increased by 0.098. The primary reason for this phenomenon may be that provinces such as Shanghai, Guangdong, and Zhejiang, located in the east, have higher levels of economic development, superior geographical positions, elevated human capital, and more comprehensive financial systems. These factors create more favorable foundational conditions for the GFD. In contrast, provinces like Xinjiang, Inner Mongolia, and Yunnan, situated in the west, have weaker levels of economic development, uneven resource allocation, and inadequate policy support, resulting in a relatively slower progress in GFD.

Furthermore, this paper has chosen the years 2008, 2015, and 2022 as observation points, employing ArcGIS software to map the evolution pattern of the GFDI for each province (See Fig. 3). The GFDI are classified into four grades: low level (0.000–0.160), lower-middle level (0.161–0.320), upper-middle level (0.321–0.480), and high level (0.481–0.640). The average values of the GFDI for each province are displayed in a radar chart (See Fig. 3). As illustrated in Fig. 3, the proportion of provinces with a high-level GFDI is progressively increasing. In 2008, there were 27 provinces at or below the lower-middle level, whereas only 3 were at or above the upper-middle level. By 2022, the number of provinces at or below the lower-middle level had decreased to 12, and those at or above the upper-middle level had increased to 18. Among these, the number of provinces at the high level had risen from 0 to 4, indicating that China's GFD is shifting from a pattern of widespread low-level regions to a spatial layout characterized by concentrated high-level regions. Additionally, in 2008, all three provinces at or above the upper-middle level were situated in the eastern region, while all five provinces at the lower level were in the western region. By 2022, 90.9% of the provinces in the eastern regions had a GFDI at the upper-middle level or above, whereas in the western region, 54.5% of the provinces had a GFDI at the lower level or below. As illustrated in Fig. 3, the GFDI of Xinjiang, Inner Mongolia,

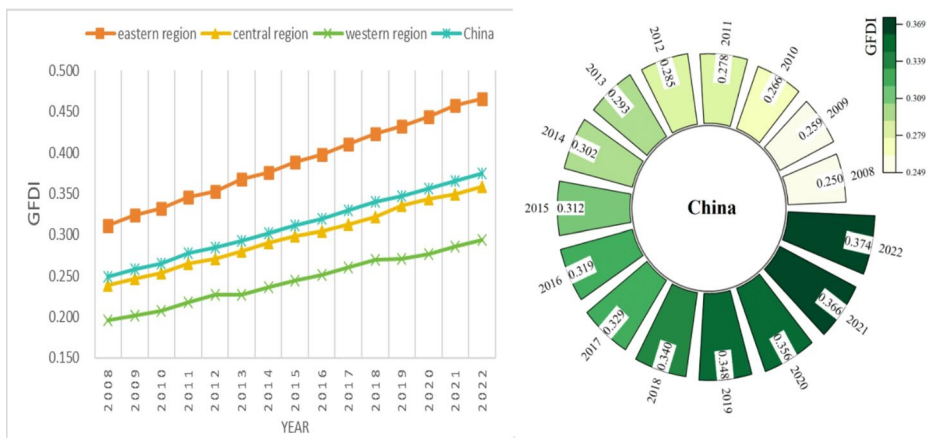


Fig. 2 Mean value of the GFDI

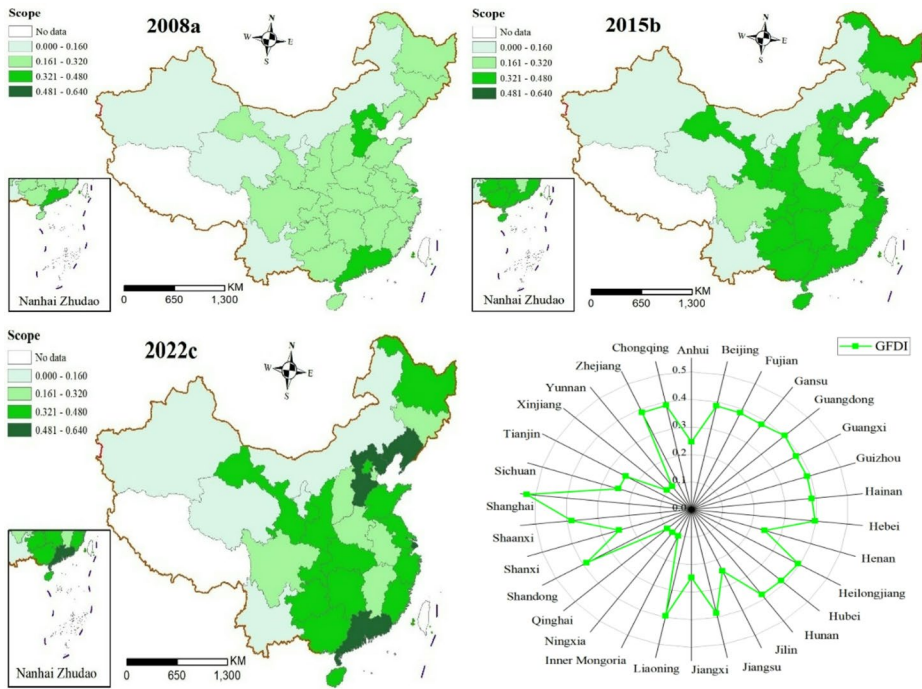


Fig. 3 Spatial distribution of the GFDI and Mean value by province

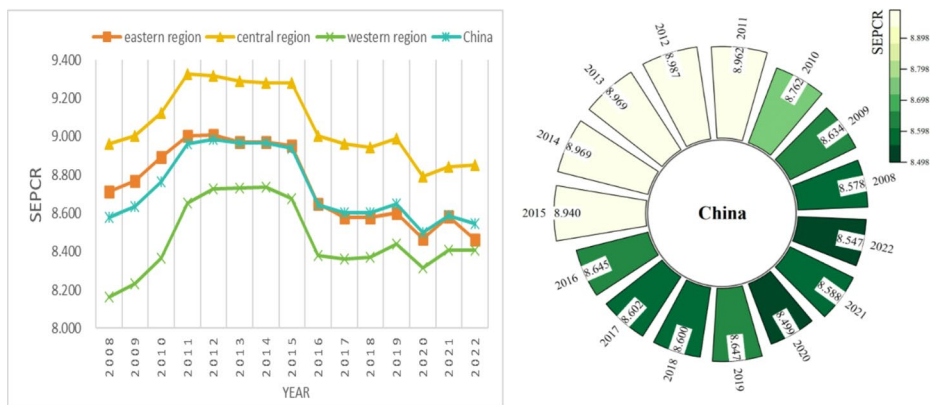
and Yunnan is significantly lower than the national average, with the maximum difference between provinces reaching 0.425 (See Table 4). This indicates that the GFDI in China is clearly polarized.

4.1.2 Analysis of the spatial-temporal of SEPCR in China

Figure 4 illustrates that the index of SEPCR in China initially rises and subsequently declines. At the national level, the SEPCR increased from 8.578 in 2008 to 8.969 in 2013, before decreasing to 8.547 in 2022. This indicates an initial enhancement in China's SEPCR. At the regional level, the SEPCR in both the eastern and central regions have declined. The SEPCR in eastern region decreased from 8.712 in 2008 to 8.462 in 2022, while the SEPCR fell from 8.964 in 2008 to 8.853 in 2022. Although the central regions have improved, they remain above the national average, with the gap between the eastern and central region gradually widening. However, the SEPCR in western regions exhibits an upward trend, increasing from 8.162 in 2008 to 8.410 in 2022. This suggests that there are regional disparities in SEPCR in China, and the degree of improvement varies significantly. The primary reason for this phenomenon could be that the eastern regions has a higher level of economic development, relies more on services and high-tech enterprises, and enforces stricter environmental regulations on high-emission industries, creating a crowding-out effect. In contrast, the central and western regions depend more on traditional industrial enterprises, with relatively lenient oversight of high-emission industries, and the spatial relocation of

Table 4 The GFDI of representative provinces

Region		2008	2015	2022
Eastern regions	Shanghai	0.408 (upper-middle level)	0.529 (high level)	0.632 (high level)
	Guangdong	0.328 (upper-middle level)	0.400 (upper-middle level)	0.483 (high level)
	Hebei	0.321 (upper-middle level)	0.397 (upper-middle level)	0.483 (high level)
	Liaoning	0.310 lower-middle level	0.393 (upper-middle level)	0.480 (high level)
Western regions	Xinjiang	0.088 (low level)	0.103 (low level)	0.135 (low level)
	Inner Mongolia	0.086 (low level)	0.105 (low level)	0.116 (low level)
	Yunnan	0.079 (low level)	0.096 (low level)	0.128 (low level)
National average		0.249 (lower-middle level)	0.312 (lower-middle level)	0.374 (upper-middle level)

**Fig. 4** Mean value of the SEPCR

traditional industries to the central and western regions has resulted in persistently high emissions of pollutants and CO₂.

Selecting the years 2008, 2015, and 2022 as observation points, the evolution pattern of SEPCR in each province was further mapped using ArcGIS software (see Fig. 5). The index is categorized into four levels: low synergy (9.001–12.000.001.000), lower-middle synergy (6.001–9.000.001.000), higher-middle synergy (3.001–6.000.001.000), and high synergy (0.000–3.000). The average values of the synergistic effects index for each province are presented in a radar chart format (see Fig. 5). From Fig. 5, it is evident that the SEPCR in China initially exhibited a severe trend before easing, with low index regions initially expanding across contiguous areas before gradually contracting. In 2008, there were 10 provinces with

low index, of which eastern provinces such as Zhejiang, Guangdong, and Jiangsu accounted for 60%, while western and central provinces each accounted for 20%. Only Hainan in the east and Qinghai in the west were at or above higher-middle levels. By 2022, the number of provinces at low index had increased to 12, with the proportion of eastern provinces decreasing to 41.7%, while the proportion of western provinces increased to 33.3%, and that of central provinces to 25%. Those at or above higher-middle levels included Hainan and Beijing in the east (See Table 5). This indicates a trend of spatial transfer of China's SEPCR towards central and western regions, particularly towards the less economically developed western regions, where the spatial evolution of SEPCR is most pronounced.

4.2 Empirical analysis

4.2.1 Benchmark regression results

The estimation results shows in Table 6, which illustrate the impact of GFD on the SEPCR within individual and time fixed effects models. Column (1) demonstrates that the impact of GFD on the SEPCR is negative. Columns (2) to (4) show the results after sequentially adding control variables, revealing that the impact of GFD on SEPCR continues to be significantly negative, with minimal alteration in the coefficients' magnitude. This implies that GFD can improve SEPCR, thereby confirming Hypothesis 1. Column (4) shows that transportation infrastructure, fiscal capacity, economic development, human capital, and industrial development all exert significant effects on SEPCR. Notably, the impact of human capital is negative, indicating that enhanced education levels can significantly improve SEPCR. Conversely, the coefficients for regional economic development, industrial development, and transportation infrastructure are positive. The potential reason for this is that the energy

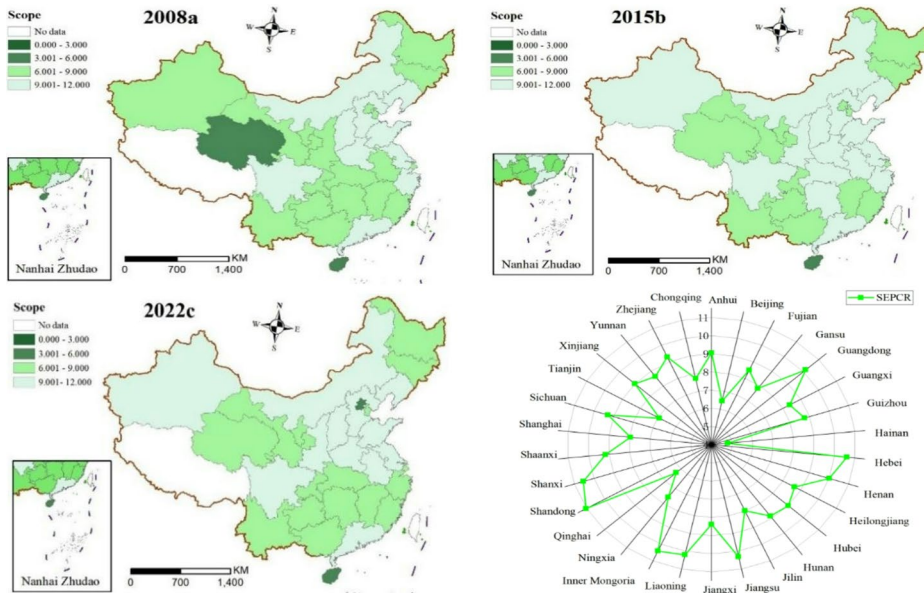


Fig. 5 Spatial distribution of SEPCR and mean value by province

Table 5 The SEPCR of representative provinces

Region		2008	2015	2022
Eastern regions	Beijing	6.808 (lower-middle synergy)	6.651 (lower-middle synergy)	5.862 (higher-middle synergy)
	Hainan	4.301 (higher-middle synergy)	5.019 (higher-middle synergy)	4.855 (higher-middle synergy)
	Zhejiang	9.344 (low synergy)	9.431 (low synergy)	8.990 (lower-middle synergy)
Central regions	Anhui	8.713 (lower-middle synergy)	9.301 (low synergy)	9.047 (low synergy)
Western regions	Shaanxi	8.883 (lower-middle synergy)	9.499 (low synergy)	9.023 (low synergy)
	Xinjiang	8.179 (lower-middle synergy)	9.409 (low synergy)	9.053 (low synergy)
	Qinghai	5.184 (higher-middle synergy)	6.621 (lower-middle synergy)	6.665 (lower-middle synergy)

currently required to sustain socio-economic development and normal living standards predominantly originates from fossil fuels, which produce CO₂ and pollutant emissions.

4.2.2 Endogeneity analysis

To circumvent potential endogeneity bias from unobservable variables, this paper employs instrumental variable method to enhance the reliability of research findings. The study selects two instrumental variables: firstly, drawing from the research approach of Li et al. (2024), the lagged one-period GFDI is utilized (IV1); secondly, it employs the interaction term between the spherical distance from each province to Shanghai and the annual average value of the GFDI, excluding that province (IV2). The closer a province is to Shanghai, the higher its expected level of economic development, which also suggests a relatively higher level of GFD, thus fulfilling the correlation criteria for instrumental variables. Additionally, the distance to Shanghai does not directly impact SEPCR within the province, thereby satisfying the exogeneity criteria for instrumental variables. Table 7 indicates that in the first-stage regression, both instrumental variables and GFD exhibit significant effects, and The Kleibergen-Paap rk LM statistic is significantly positive. The Gragg-Donald Wald F and Kleibergen-Paap Wald F statistics both surpass the critical value reject the weak instrumental variable test, suggesting that the IV1 and IV2 effectively meet the identification and exogeneity requirements. After further controlling for endogeneity bias, the results demonstrate that the negative impact of GFD on SEPCR remains significant, with minimal change in the estimated coefficient magnitude, further confirming the results are robust.

Table 6 The results of benchmark regression

Variable	SEPCR			
	(1)	(2)	(3)	(4)
<i>GFDI</i>	-6.506*** (-10.96)	-5.925*** (-10.14)	-5.869*** (-10.11)	-5.640*** (-9.18)
<i>Jtss</i>		0.789*** (5.44)	0.611*** (3.90)	0.592*** (3.69)
<i>Cznl</i>		1.221*** (3.24)	1.587*** (3.98)	1.801*** (4.39)
<i>pijs</i>			-0.098 (-1.45)	-0.111 (-1.64)
<i>pgdp</i>			0.369*** (2.60)	0.329** (2.10)
<i>Sjyl</i>				-3.961* (-1.96)
<i>Gysp</i>				0.868** (2.02)
<i>Opcd</i>				-0.038 (-0.30)
<i>Constant</i>	10.201*** (66.89)	0.770 (0.45)	-0.317 (-0.16)	0.026 (0.01)
<i>Provincial-fixed effect</i>	Yes	Yes	Yes	Yes
<i>Time-fixed effect</i>	Yes	Yes	Yes	Yes
<i>Observations</i>	450	450	450	450
<i>R²</i>	0.538	0.577	0.586	0.595

***, ** and * indicate the significance level of 1%, 5% and 10% respectively; the standard error of robustness is in parentheses. The same below

4.2.3 Robustness analysis

Adjust the sample Considering the potential impact of the COVID-19 pandemic on fiscal policies across regions, which may alter the supply structure and usage direction of GF funds in the short term, thereby affecting the development and effectiveness of GF in various provinces, and given that the phased suspension of industrial production and transportation activities during the pandemic led to abnormal fluctuations in pollutant and CO₂ emissions, this study excludes data from 2019 to 2022 and re-estimates. The results in Table 8, column (1), indicate that the impact of GFD on the SEPCR remains significantly negative. Additionally, to mitigate the influence of extreme outliers, this study applies truncation to the GFDI at the 1% and 5% levels and re-estimates. Columns (2) and (3) in Table 8 show that the impact of GFD on SEPCR remains significantly negative. This suggests that, even after adjusting the sample's time span and truncating the data, the regression results are robust.

Excluding the impact of other policies The SEPCR in a city are also influenced by other related environmental governance policies. The carbon emission trading policy is an key tool for China to address climate change. Since 2013, seven provinces and municipalities, including Beijing and Shanghai, have successively implemented carbon emission trading pilot policies. Relevant studies have also shown that this policy is capable of significantly reducing the total emissions of environmental pollutants and CO₂ (Zhang et al., 2019; Shao

Table 7 Results of endogenous test

Variable	IV1-2SLS		IV2-2SLS	
	stage I	stage II	stage I	stage II
<i>IV</i>	0.805*** (0.03)		-0.282*** (0.03)	
<i>GFDI</i>		-6.296*** (0.98)		-7.305*** (1.29)
<i>Control variables</i>	Yes	Yes	Yes	Yes
<i>Provincial-fixed effect</i>	Yes	Yes	Yes	Yes
<i>Time-fixed effect</i>	Yes	Yes	Yes	Yes
<i>Observations</i>	420	420	450	450
<i>R²</i>	0.995	0.530	0.987	0.533
<i>Kleibergen-Paap rk LM statistics</i>	92.809[0.000]		26.888[0.000]	
<i>Cragg-Donald Wald F statistics</i>	679.725{16.380}		103.473{16.380}	
<i>Kleibergen-Paap rk Wald F statistics</i>	554.620{16.380}		90.783{16.380}	

[] is the p value, and { } is the critical value of Stock-Yogo weak identification test at the 10% level

Table 8 Results of robustness test

Variable	(1)	(2)	(3)	(4)	(5)	(6)
	Important event	1% shrinkage tailing	5% shrinkage tailing	Other policy	Pollution Emissions	CO ₂ Emissions
<i>GFDI</i>	-7.474*** (-9.70)	-5.648*** (-9.17)	-4.441*** (-7.76)	5.440*** (-8.65)	-0.729*** (-6.64)	-1.608*** (-4.79)
<i>Constant</i>	-3.751 (-1.43)	-0.152 (-0.07)	-0.484 (-0.22)	0.619 (0.27)	1.204*** (-2.84)	6.775*** (5.23)
<i>controlled variable</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Provincial-fixed effect</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Time-fixed effect</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Observations</i>	360	450	450	345	450	450
<i>R²</i>	0.622	0.595	0.573	0.635	0.685	0.598

et al., 2023). Therefore, to avoid interference from policy synergies with other major policies during the same period on the research results, this study further excludes the provinces with carbon emission trading pilot policies from the analysis. As shown in column (4) and column (5) of Table 8, the coefficients remain significantly negative.

Replace the dependent variable To prevent potential bias in the results due to data dependency, we have altered the measurement method of the dependent variable for a robustness check. Referencing the research by Tan et al. (2024), this paper substitutes the SEPCR with the environmental pollution index and CO₂ emissions for robustness testing. The coefficients of GFD on the environmental pollution index and CO₂ emissions remain significantly

negative (See Table 8), further demonstrating that the benchmark regression estimates possess good robustness.

4.2.4 Heterogeneity analysis

Heterogeneity based on varying levels of financial development GFD and its environmental impact necessitate a certain degree of financial development as a foundation. Referencing the research by Yu et al. (2022), the study measures the level of financial development using the ratio of financial institution loan balances to GDP and categorizes samples based on the median for regression analysis. Columns (1) and (2) in Table 9 show GFD has a significant negative impact on the SEPCR, suggesting that under different levels of financial development, GFD can significantly improve the SEPCR. However, the coefficient of GFD is larger at higher levels of financial development, implying that the more developed the urban financial sector, the more comprehensive the institutional framework for GFD becomes, which in turn is more beneficial for enhancing the SEPCR.

Heterogeneity based on varying levels of informatization technology development The SEPCR are influenced by the level of urban informatization technology development. This study use the ratio of post and telecommunications business volume to GDP to measure the level of informatization technology development, and groups samples according to the median for regression analysis. Columns (3) and (4) of Table 9 reveal that the impact of GFD on the SEPCR is negative. The higher the level, the more efficiently GFD can serve the green economy through digital means. In addition, by strengthening the construction of corporate environmental information disclosure platforms, broadening information collection channels, improving information acquisition efficiency, and perfecting supervision and management systems, phenomena such as “greenwashing” can be reduced, thereby enhancing the SEPCR.

Heterogeneity based on varying intensities of environmental governance The intensity of environmental governance reflects a city’s commitment to ecological and environmental

Table 9 Results of heterogeneity analysis 1

Variable	(1)	(2)	(3)	(4)
	Low financial development level	High financial development level	Low level of information technology	High level of information technology
<i>GFDI</i>	−3.528*** (−3.84)	−3.969*** (−3.97)	−3.267*** (−3.56)	−6.700*** (−7.61)
<i>Constant</i>	3.360 (0.93)	−6.387* (−1.77)	0.562 (0.17)	0.025 (0.01)
<i>controlled variable</i>	Yes	Yes	Yes	Yes
<i>Provincial-fixed effect</i>	Yes	Yes	Yes	Yes
<i>Time-fixed effect</i>	Yes	Yes	Yes	Yes
<i>Observations</i>	225	225	225	225
<i>R²</i>	0.713	0.669	0.670	0.551

protection, and it may influence the impact of GFD on the SEPCR. This paper evaluates environmental governance intensity by examining local fiscal expenditure on environmental protection (in billion yuan), categorizing it into high, medium, and low environmental governance groups from highest to lowest. Table 10 indicates that under low environmental governance intensity, the impact of GFD on the SEPCR is positive but insignificant. However, under medium and high environmental governance intensity, the impact of GFD is significantly negative. Moreover, as environmental governance intensity increases, the impact becomes more pronounced. The potential reason is that greater investment in environmental governance signifies a stronger governmental commitment to environmental protection and stricter environmental regulations, which increases the likelihood of GFD being allocated to green industries, and enhances the SEPCR. Conversely, inadequate regulatory efforts for environmental governance may lead to “greenwashing,” misallocation of financial resources, and other adverse phenomena, causing funds to be directed into non-green industries. This directly impacts the effectiveness of GFD in reducing pollutants and CO₂ emissions.

4.2.5 Mechanism analysis

During the source governance phase, green finance tends to invest in green industries, driving upgrades in the industrial structure. This, in turn, has a direct impact on the SEPCR. Table 11 indicates that the impact of GFD on ISU is positive, suggesting that GFD can substantially promote such upgrades. Extensive research also supports the notion that ISU can enhance the SEPCR in cities (He et al., 2023). These upgrades can reduce the proportion of extensive and labor-intensive industries, minimize mismatches in production factors and resource energy consumption, thereby improving the SEPCR. Additionally, they can drive the upgrading of energy consumption structures, increasing the share of clean energy sources, thus reducing pollutants and CO₂ emissions. In eastern coastal provinces, green finance facilitates the transition of traditional industries by supporting high-tech manufacturing and modern service sectors. In central and western regions, it drives industrial restructuring through spatial relocation, with a focus on greening traditional energy industries. Green finance prioritizes clean coal utilization and ecological restoration, such as promoting clean energy alternatives in resource-dependent provinces.

During the process control phase, GFD can foster the GTI and enhance EUE, and further affects the SEPCR. The findings in Table 11 indicate that GFD can stimulate GTI and

Table 10 Results of heterogeneity analysis 2

Variable	(1)	(2)	(3)
	Low environmental governance	Medium environmental governance	High environmental governance
<i>GFDI</i>	0.279 (0.19)	-4.759*** (-3.33)	-7.774*** (-5.90)
<i>Constant</i>	-9.269** (-2.35)	-4.301 (-0.90)	0.337 (0.07)
<i>Controlled variable</i>	Yes	Yes	Yes
<i>Provincial-fixed effect</i>	Yes	Yes	Yes
<i>Time-fixed effect</i>	Yes	Yes	Yes
<i>Observations</i>	150	150	150
<i>R²</i>	0.748	0.627	0.771

Table 11 Results of moderating effect test

Variable	Source governance phase	Process control phase		End-of-pipe governance stage
	ISU	GTI	EUE	IER
<i>GFDI</i>	2.143*** (5.92)	0.508*** (3.18)	8.272*** (6.77)	0.059*** (3.06)
<i>Constant</i>	-2.800** (-2.20)	1.385** (2.46)	-13.089*** (-3.05)	0.092 (1.36)
<i>controlled variable</i>	Yes	Yes	Yes	Yes
<i>Provincial-fixed effect</i>	Yes	Yes	Yes	Yes
<i>Time-fixed effect</i>	Yes	Yes	Yes	Yes
<i>Observations</i>	450	450	450	450
<i>R²</i>	0.859	0.483	0.802	0.309

improve EUE. Extensive research also supports this conclusion (Shao et al., 2022). Boosting GTI and improving EUE can lower energy consumption and emissions, thus reducing total pollutants and CO₂ emissions. The decrease in total emissions can also decrease the overall cost for enterprises to mitigate emissions, thereby heightening their motivation for green production. Core urban clusters like Shanghai primarily depend on green technology innovation, exhibiting spatial clustering and knowledge spillover characteristics. With their concentration of talent, capital, and research institutions, these cities prioritize building innovation ecosystems, exemplified by science and technology innovation funds. In contrast, resource-based cities such as Shanxi focus on cleaner fossil fuel utilization, while industry-dominated provinces like Shandong enhance industrial energy efficiency. By adopting technology imports and other measures, they compensate for insufficient endogenous innovation to improve energy utilization efficiency.

At the end-of-pipe governance stage, GFD influences the SEPCR by strengthening the IER. Table 11 shows that GFD can substantially enhance the IER. Meanwhile, numerous studies have the same conclusions (Liu et al., 2024a, b; Sun et al., 2024). Environmental regulation can reduce CO₂ and pollutant emissions by compelling enterprises to bear the costs of external emission control, adjusting market consumption preferences, and controlling resource allocation rules. The market-oriented cities mainly regulate the enterprises by market, and guide the enterprises to reduce pollution and carbon emissions through price signals, forcing the enterprises to transform and upgrade. For example, the pilot carbon financial derivatives in Shanghai Free Trade Zone.

4.2.6 Threshold analysis

The impact of GFD on the SEPCR may exhibit a nonlinear trend. To further verify the nonlinear influence of different levels of GFD, this paper employs the GFDI as a threshold variable for threshold regression analysis and utilizes Bootstrap sampling to simulate likelihood ratio statistics 300 times to determine the number of thresholds. Table 12 indicates that the single-threshold effect of GFD is exist, suggesting that the impact of GFD on the SEPCR has a single-threshold effect, with a threshold value of 0.0961.

Table 12 Threshold number tests

Threshold variable	Null hypothesis	Threshold value	Siding-to-siding block	<i>P</i> value
<i>GFDI</i>	Single threshold	0.096**	[0.094,0.170]	0.033
	Double threshold	0.252	[0.246,0.254]	0.170

Table 13 Threshold regression results

Threshold variable	SEPCR
$GFDI \leq 0.0961$	-8.839***(-11.18)
$GFDI > 0.0961$	-4.898***(-5.39)
<i>Constant</i>	-0.379*(-1.76)
<i>controlled variable</i>	Yes
<i>Provincial-fixed effect</i>	Yes
<i>Time-fixed effect</i>	Yes
<i>Observations</i>	450
R^2	0.625

Table 13 show that the impact of GFD on the SEPCR exhibits nonlinear characteristics. When GFDI is below the threshold value of 0.0961, the threshold regression coefficient is -8.839. When GFDI exceeds this threshold value, the regression coefficient becomes -4.898. This indicates that when GFDI surpasses the threshold, its impact on the SEPCR weakens. The possible reasons include the influence of economic development, resource allocation, human capital, and environmental regulations on the effectiveness of GFD. When these external factors do not match the level of GFD development, their impact on the SEPCR will weaken.

5 Discussion

5.1 Form a supervision and management mechanism involving multiple stakeholders

Establish and improve GFD policy system, forming a supervision and management mechanism involving multiple stakeholders including government departments, financial institutions, the public, and enterprises (Johri et al., 2024). First, refine the GFD policy framework to develop comprehensive evaluation criteria for green and low-carbon projects, ensuring precise and efficient resource allocation. Second, innovate GFD products and tools to diversify financial service offerings, meeting the varied needs of resource allocation. Finally, to bolster the risk management and control capabilities of financial institutions, it is crucial to enhance the development of professional teams and utilize technologies such as big data and artificial intelligence. Concurrently, it is essential to improve the information disclosure level, establishing a transparent and reliable mechanism for tracing the flow of green funds. This approach will effectively curb the emergence of inappropriate practices, such as “greenwashing.” Additionally, it will ensure the sustainability of the GFD system.

5.2 Develop green finance in a location-specific manner

Develop green finance in a location-specific manner, providing targeted policy support to each region. GFD should consider the disparities in regional resource endowments, levels of financial development, penetration of information technology, and the intensity of environmental regulation, rather than adopting a one-size-fits-all approach. For instance, traditional energy regions such as Shanxi should prioritize transition finance policies to support the development of photovoltaic industries in abandoned mining areas. In contrast, developed regions like Zhejiang should concentrate on fostering green supply chain finance to promote green production throughout industrial chains. India advocates a market-driven innovation model, featuring renewable energy certificate trading and high market flexibility. Brazil relies on international climate finance instruments, emphasizing collaborative ecological protection financing. South Korea focuses on intensive industries to enhance technological integration. Meanwhile, to maximize the effectiveness of GFD, regions should focus on improving their own financial capabilities, information technology levels, and environmental regulation intensity.

5.3 Focus on the role of ISU, GTI, EUE and IER

Focus on the role of ISU, GTI, EUE and IER in the impact of GFD on the SEPCR. In the source prevention phase, accelerate ISU and promote a clean energy transition. While paying attention to the green development of industries, it is also essential to ensure the rationality of the industrial structure, avoiding excessive pursuit of green and low-carbon goals that could inhibit economic development efficiency. For example, Europe's aggressive measures to transition to green energy have led to a severe energy crisis, directly impacting the stable and orderly development of its economy. In the process control phase, expedite the advancement of GTI and improve EUE. Emphasize the optimization and innovation of existing equipment and technical processes, and appropriately introduce advanced technology, equipment, and talent. In the end-of-pipe treatment phase, To maximize the scale effect of resources and equipment, the government should allocate environmental governance funds rationally and co-construct regional sewage treatment centers and other infrastructure. Additionally, smooth public supervision channels should be established, incentives such as rewarded reporting set up, and social supervision synergy formed.

6 Conclusion

This paper analyzed the spatial-temporal pattern evolution of the GFDI and SEPCR. The study reveals the impact of GFD on the SEPCR and the threshold effect. The findings are as follows: (1) GFD is continuously improving, exhibiting a regional characteristic of "eastern regions > central regions > western regions," with regional development becoming increasingly polarized. The SEPCR first increases and then decreases, presenting a regional characteristic of "central regions > eastern regions > western regions"; the synergistic effects in the eastern and central regions have improved, but they are weakening in the western regions. (2) GFD can enhance the SEPCR, but as GFD reaches a certain value, its impact gradually diminishes, exhibiting a non-linear influence characterized by increasing marginal utility

followed by decreasing marginal utility. This result remains valid after a series of robustness tests. (3) Heterogeneity tests show that the impact of GFD on the SEPCR is more significant under high levels of financial development, high levels of informatization, and strong environmental governance. (4) GFD enhances the SEPCR through four pathways: ISU, GTI, EUE, and IER.

6.1 Limitations

Despite the aforementioned research findings, this study still has several notable limitations that provide reference directions for future research. At the data level, the interpolation method used in data processing may introduce measurement errors, affecting the accuracy of data analysis results. Future studies could incorporate prefecture-level city and micro-enterprise data into the research. Regarding analytical methods, this paper only examines regional differences at the data level without conducting empirical analysis on spatial effects. Future research could introduce spatial analysis models to explore spatial spillover effects. In terms of analytical scope, this study only analyzed the exclusion of synergistic effects between other policies without exploring their interactive relationships. Future research could conduct empirical analysis on synergistic or mutually exclusive effects between policies to achieve better policy implementation outcomes. Additionally, although four major communication channels were identified from the perspective of whole-process governance, other potential mechanisms still exist and require further exploration.

Data Availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

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