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The Impact of Green Finance on Regional Total Factor Productivity

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Abstract: Guided by the dual carbon goals of peaking emissions and achieving carbon neutrality, Guangdong Province, as the vanguard of China's reform and opening-up, offers valuable green finance development experiences that are of reference significance for South China and nationwide. Utilizing panel data from 21 prefecture-level cities in Guangdong (2000-2019), this study employs the entropy method and stochastic frontier analysis (SFA) to calculate a city-level Green Finance Development Index (GF) and Total Factor Productivity Change (TFPC). A two-way fixed effects panel model is then applied to empirically analyze the impact mechanisms of green finance on regional productivity. By decomposing total factor productivity into technological progress (TC), technical efficiency change (TEC), scale efficiency change (SC), and allocative efficiency change (AEC), the research delves into the operational pathways of green finance. Results show its complex, multidimensional effects: while it limits technical and scale efficiency, it significantly enhances technological progress and resource allocation efficiency.

Keywords: Green Finance; Total Factor Productivity; Stochastic Frontier Analysis; Sustainable Development

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1. Introduction

With rapid economic development, environmental degradation, ecological deterioration, and resource scarcity have become increasingly prominent, making green development a critical agenda in national development strategies. During the National Ecological Conservation Conference in July 2023, China's head of state emphasized the need to refine economic policies supporting green and low-carbon development through enhanced fiscal, tax, financial, and pricing measures to accelerate the society-wide green transition. In recent years, the Chinese government has progressively enhanced its green finance policy system, utilizing novel instruments such as carbon emission reduction facilities to channel financial resources into clean energy and energy efficiency sectors, thereby creating new drivers for high-quality economic growth. China's economic growth model has transitioned from the extensive expansion during the planned economy era, to factor-driven growth following reform and opening-up, and subsequently to innovation-driven growth in the new era. This transition has seen total factor productivity improvements become the fundamental force propelling high-quality economic growth. As a crucial element of China's economic competitive advantage, green finance now acts as a key catalyst for driving the progress of contemporary national economic development.

A pioneer in China's economic reform, Guangdong has balanced growth with ecological goals, emerging as an innovator in green finance. In 2017, the PBOC Guangzhou Branch launched the "Single Hub, Dual Spheres" framework, centering on the Guangzhou Green Finance Innovation Pilot Zone. This model leverages Greater Bay Area connectivity and spatial linkages to spur provincial green finance development. Coupled with the 2023 Carbon Peak Plan's strategic measures, green finance is now central to Guangdong's low-carbon transition. Through sustained supply-side reforms over the past decade, the province has made significant advances in green finance innovation. As a key tool for sustainable development, green finance promotes high-quality growth and shows strong potential to boost regional total factor productivity (TFP), a core efficiency metric that informs policy and resource optimization. The critical role of green finance in the Bay Area's carbon neutrality efforts underscores the importance of studying Guangdong's mechanisms and their TFP effects, an inquiry with considerable academic and policy value.

Against this backdrop, this study empirically analyzes the impact of green finance development on total factor productivity (TFP) and its underlying mechanisms, using panel data from 21 prefecture-level cities in Guangdong Province (2000–2019). Our primary objectives and key contributions are threefold. First, by deconstructing the green finance system into seven key components, we systematically examine their potential effects on TFP. This analysis provides both theoretical support and empirical evidence for the effective implementation of regional green finance policies. Second, moving beyond the conventional three-component decomposition of TFP, which comprises technological progress, technical efficiency, and scale efficiency, this paper introduces allocative efficiency as a fourth dimension. It further explores how green finance development affects local resource allocation efficiency, thereby establishing a more comprehensive, four-dimensional analytical framework. Third, we elucidate the pathway mechanisms through which green finance influences productivity in Guangdong. These findings offer substantial financial policy insights for advancing the Green and Beautiful Guangdong Initiative and the national “Dual Carbon” strategy, thereby contributing to sustainable green finance development.

2. Theoretical Analysis and Hypotheses Development

Financial development is closely tied to economic growth, with green finance increasingly becoming a crucial driver for sustainable development. Decision-makers and policymakers in developing countries need to acknowledge the importance of financial development and its role in the economic growth process, as it impacts employment, population, inequality, and poverty (Chavriya et al., 2024). While focusing on development, constructing a well-rounded financial development system can reduce ecological footprints, with this effect being particularly evident in both developing and developed nations (Aslam et al., 2023). Along with a solid financial development framework, financial innovation and the quality of financial institutions are key factors influencing economic development. Strong financial innovation promotes financial growth, while lower institutional quality in emerging markets can hinder this development (Alawi et al., 2022). The rise of green finance has brought new energy to the socio-economy, offering fresh perspectives for individuals, businesses, financial institutions, and policymakers. As early as the 1990s, environmental protection and social responsibility began to gain attention in foreign businesses and the financial sector. People started realizing the impact of financial activities on the environment and society, and the concept of green finance gradually evolved and matured. The development of green finance has become the first step in enhancing sustainability in capital markets, changing the interaction patterns among market participants (Maltais & Nykvist, 2021). These shifts in interaction have impacted the sustainability of internal business operations. This influence, however, extends beyond individual companies and affects economies in a multidimensional manner. Falcone (2020) suggests that the development of green finance not only accelerates the transition of economies to sustainable development but also creates favorable conditions to ensure a fair competitive environment for both traditional and green economies. Furthermore, any support from green finance tools is likely to raise regional GDP per capita, both in the short and long term (Rasoulinezhad & Taghizadeh-Hesary, 2022).

It is easy to see that the development of green finance has some positive impacts on economic growth, including attracting investment resources, enhancing regional economic competitiveness, optimizing industrial structure transformation, promoting ecological improvement, creating new jobs, and boosting international competitiveness (Wei, 2024). First, green finance directly influences the movement of market funds and resources. Within the context of green finance, financial institutions help improve economic quality by optimizing the direction of credit allocation. Relevant policies guide financial capital into environmental protection and green construction, promoting urban transformation and upgrading. De Haas & Popov (2023) studied how the financial structures of different countries affect the green transformation of industries. They found that the stock market promoted green innovation in carbon-intensive sectors, reducing carbon emissions per unit of output and reallocating investments to more energy-efficient industries, underscoring the critical role of capital markets in promoting green finance and resource allocation. Thus, advancing green finance requires leveraging capital markets and capital's dominant role in resource allocation. Capital's leading role drives resources toward green development, channeling more funds into environmental industries and indirectly contributing to green economic development. This process, involving the allocation of green finance funds and industrial upgrades, directly fuels high-quality green economic growth and regional ecological improvement (Yang, 2023).

Moreover, green finance mobilizes savings, allowing financial institutions to attract more deposits, ensuring capital formation, and optimizing factor allocation across industries. This increases capital efficiency, enabling enterprises to invest more in technology adoption and transformation, thus raising regional innovation and management levels (Palmaccio et al., 2023). This indirectly reflects that green finance policies can directly influence businesses. The implementation of these policies increases capital accessibility for enterprises, lowers financing costs, and facilitates technological progress through adjusted innovation input structures. Luo & Wang (2024) found that green finance development lowered the capital threshold for the commercialization of research outcomes in intermediate product enterprises, raising demand for patent technology. At the same time, the commercialization cycle of research results shortened, enhancing research efficiency and output in R&D departments. Zhang et al. (2024) discovered a positive correlation between corporate green innovation and skill premiums. Their analysis emphasized the significant role of green finance policies in increasing the use of skilled labor, especially in highly urbanized areas. As companies use more capital, they increase demand for skilled labor, which raises skill premiums, attracting labor from surrounding areas to regions with more advanced financial development, thus influencing changes in regional labor factors.

On the flip side, the rapid development of green finance may also bring some potential drawbacks to economic growth. Because the development of green finance requires significant investment and innovation, society faces economic fluctuations while the demand for patented technology and different labor factors in regions continues to increase, which may exacerbate the shortage and competition for funds and talents, thereby hindering the green transition of traditional enterprises. He et al. (2022) found that in the process of promoting the green transition of enterprises, the effect of green finance on optimizing the economic structure is not as significant as expected. The rapid advancement of policies has instead imposed very high transition costs on traditional enterprises that support the national economy and weakened confidence in the green transition. The inflow of green funds is often biased, and traditional enterprises and non-energy-saving environmental protection enterprises usually find it difficult to obtain sufficient financial support, thus facing external financing constraints (Matteo et al., 2023). This increases their R&D costs, causing them to gradually lose confidence in the transition, negatively affecting the overall economic growth of the region. For different types of enterprises, the vigorous development of green finance may also have varying degrees of negative impact. Especially for high-pollution enterprises, the rapid advancement of green finance-related policies has subjected them to credit constraints and increased their exit risk, while also inhibiting their technological innovation (Zhang et al., 2024). Even though the relevant policies have improved the investment efficiency of some enterprises, they have suppressed the performance of others, indirectly inhibiting the total factor productivity of enterprises. Therefore, the development of green finance will not only positively impact economic development but may also present obstacles. Thus, we propose:

Hypothesis 1a (H1a): The development of green finance in Guangdong Province has a positive impact on regional total factor productivity;

Hypothesis 1b (H1b): The development of green finance in Guangdong Province negatively impacts regional total factor productivity.

In recent years, various studies have emerged exploring the relationship between green finance and economic growth, with varying conclusions. Therefore, the impact of green finance on total factor productivity growth is likely to be integrated and complex, necessitating a clear understanding of its mechanisms and their heterogeneity. Based on the work of Kumbhakar & Lovell (2000), this paper decomposes total factor productivity into four components: technological progress, technical efficiency, scale efficiency, and allocative efficiency. The paper examines the impact of green finance on each of these components and constructs a theoretical framework for analyzing the relationship between green finance and regional total factor productivity from an empirical perspective.

First, technological progress plays a crucial role in sustainable economic development and is a key factor in reducing energy consumption in businesses. It relies on the efficient allocation of funds and innovation in technology research and development. Technological progress is not only essential for improving energy efficiency across industries but also a significant determinant of socio-economic growth, interacting with energy consumption and human capital (Oliveira et al., 2024). The development of green finance allows enterprises to access funds more easily and at lower costs, enabling them to invest more in structural adjustments, which leads to changes in regional technological progress. With the support of green funds and policies, enterprises are encouraged to research, introduce, and apply environmentally friendly and sustainable technologies, which in turn promotes regional technological innovation and progress (Wu et al., 2022). Additionally, green finance supports the improvement of services and products offered by financial institutions, fostering innovation and enabling the creation of more diverse green financial products. High-quality and dynamic financial institutions are crucial for ensuring financial stability and long-term sustainable development, as well as aligning financial development with economic policies for coordinated growth (Sajid et al., 2023). Given this, does the support from green funds and policies have a positive impact on technological progress in Guangdong, which is at the forefront of China's green finance development? According to Zeng et al. (2023), the development of green finance significantly promotes technological innovation in the environmental protection industry, reducing capital barriers and fostering technological progress. Lin, Lam et al. (2023) found that the establishment of green finance reform and innovation pilot zones has a lagged effect on promoting sustainable economic and social development. The positive impact on sustainable development is significant only in regions with lower financial development, lower industrialization, and higher technological innovation levels. On the other hand, compared to traditional financial systems, green finance systems are stricter in financing high-pollution and high-energy-consuming industries, leading to capital outflow from these sectors. Guo et al. (2024) found that financial institutions continuously raise the loan thresholds for "three high" enterprises, limiting their interest-bearing debt financing and new investments. They also set capital market indicators to guide social funds away from "three high" enterprises and toward green enterprises, further shrinking the space for high-energy-consuming, high-pollution, and high-emission enterprises. While allocating funds in the market, traditional industries receive less support compared to energy-saving and environmentally friendly industries. The costs and risks of their R&D and innovation technologies increase, so green finance may lead to capital outflows and risk aversion, thus hindering technological progress and suppressing total factor productivity. Thus, we propose:

Hypothesis 2a (H2a): The development of green finance in Guangdong Province has a positive impact on regional technological progress;

Hypothesis 2b (H2b): The development of green finance in Guangdong Province has a negative impact on regional technological progress.

Technical efficiency reflects the ability to convert inputs into effective outputs and is an important factor influencing total factor productivity. When green finance development makes it easier for enterprises to access financial support, it will inevitably affect the adjustment of their input structures and strategies, thereby impacting output and reflecting technical efficiency. The inflow of green funds alleviates the financing constraints faced by green enterprises, providing strong support for technological innovation and transformation in the green sector, as well as the introduction of advanced management models, which continuously improve technical efficiency and promote the commercialization of research outcomes, enhancing overall regional R&D efficiency (Lei et al., 2024). However, small and medium-sized enterprises (SMEs) that are not energy-efficient or environmentally friendly will be forced to transform but may not obtain sufficient financial support, resulting in high risks and uncertain returns in their innovation activities. This makes them more susceptible to external financing constraints, which limits their technological R&D efficiency in the green sector and hinders regional technical efficiency progress (Rupeika-Apoga & Petrovska, 2022). Thus, we propose:

Hypothesis 3a (H3a): The development of green finance in Guangdong Province has a positive impact on regional technical efficiency;

Hypothesis 3b (H3b): The development of green finance in Guangdong Province has a negative impact on regional technical efficiency.

The increase in capital investment is an important manifestation of the expansion of economic and production scales. The flow and allocation of funds brought about by the development of green finance undoubtedly have an impact on regional scale efficiency. Firstly, the improvement in the allocation efficiency of green credit funds across different industries has promoted the upgrading of urban industrial structures. Green credit improves the allocation efficiency of funds in the renewable energy industry, promoting its rapid development. At the same time, it produces a crowding-out effect on other traditional industries, urging them to accelerate their transformation and upgrading to meet the requirements of green development (Wang & Fan, 2023). Second, green innovative products and services satisfy consumers' diverse and multi-layered needs for sustainability, health, safety, and environmental protection, such as energy-efficient appliances, organic food, and new energy vehicles (Li & Zhang, 2023). Consumers are increasingly concerned not only with the basic functions and quality of products but also with their environmental impact and sustainability. These products and services have not only accelerated the optimization and upgrading of urban industrial structures but have also maximized scale effects and structural dividends, injecting new vitality into industrial development and improving regional total factor productivity. However, for enterprises of different scales, China's financial system has traditionally favored serving state-owned and large enterprises with lower production efficiency, some of which even face over-service. The support from green funds may cause large-scale state-owned and large enterprises to become even more bloated, deviating further from the optimal enterprise size, which could reduce regional scale efficiency (Wang & Shao, 2024). Therefore, the development of green finance does not necessarily lead to the full realization of scale efficiency. Thus, we propose:

Hypothesis 4a (H4a): The development of green finance in Guangdong Province has a positive impact on regional scale efficiency.

Hypothesis 4b (H4b): The development of green finance in Guangdong Province has a negative impact on regional scale efficiency.

The development of green finance has driven the flow and further allocation of funds and resources, while allocation efficiency reflects the effectiveness of how funds and resources are distributed within the economy. Green finance policies guide funds from high-pollution, high-energy consumption, and overcapacity industries toward green industries, while also directing capital from inefficient enterprises to more efficient ones within these high-pollution sectors. This drives the upgrading of industrial structures and urban transformation (Gu et al., 2021). As society shifts toward emerging economic models, it may also impact the resource allocation within traditional enterprises. Funds and resources tend to favor energy-saving and environmentally friendly enterprises, which can increase the cost of converting resources into output for traditional enterprises, even those with strong growth potential and development prospects but without an energy-efficient or environmentally friendly focus (Hu et al., 2024). The rapid development of green finance increases the transformation costs for traditional enterprises that support the national economy, leading to a gradual decline in their confidence in transitioning to green development. This, in turn, negatively impacts the efficiency of resource allocation within these enterprises, making both the enterprises and the region gradually deviate from the optimal allocation efficiency. Thus, we propose:

Hypothesis 5a (H5a): The development of green finance in Guangdong Province has a positive impact on regional allocation efficiency;

Hypothesis 5b (H5b): The development of green finance in Guangdong Province has a negative impact on regional allocation efficiency.

3. Study Design

3.1 Model Construction

First, a baseline econometric model is established to analyze the impact of green finance development in Guangdong Province on total factor productivity (TFP). Following the Hausman test, a fixed effects model is selected. Considering the heterogeneity across years and regions, a two-way fixed effects model is constructed as follows:

$$TFPC_{i,t} = \beta_0 + \beta_1 GF_{i,t} + \sum \beta_j Control_{it} + \gamma_t + \mu_i + \varepsilon_{i,t} \quad (1)$$

In Equation (1), the dependent variable is $TFPC_{i,t}$, the independent variable is $GF_{i,t}$, and $Control_{it}$ represents a series of control variables. γ_t denotes time fixed effects, μ_i denotes regional fixed effects for each prefecture-level city, and $\varepsilon_{i,t}$ is the random error term.

3.2 Variable Selection and Explanation

3.2.1 Sample Selection and Data Sources

Since the outbreak of COVID-19, the real economy has been severely impacted, reducing the effective labor force and indirectly disrupting the normal market transaction mechanism. The pandemic has disrupted the market economy, severely squeezing both supply and demand, which in turn affects the flow and allocation of capital in the market. The pandemic reduced the effective labor force and indirectly disrupted the normal market transaction mechanism. For the total factor productivity studied in this paper, both capital and labor, as important influencing factors, are inevitably affected by the pandemic. In addition, in terms of finance, Goldstein, Koijen & Mueller (2021) discovered that the pandemic led to an increase in unemployment rates, which triggered higher default rates in lending, thereby increasing financial risks and seriously impacting financial institutions and the macroeconomy. Moreover, the uncertainty caused by the pandemic also affected investor sentiment and led to changes in corporate stock prices (Kirci Altinkeski, Cevik & Dibooglu, 2022; Al-Yahya, 2022). Therefore, to ensure the reference value of the research results, this study excludes the years of the pandemic and post-pandemic period, focusing on the period from 2000 to 2019 for the 21 prefecture-level cities in Guangdong Province, to explore whether the promotion of green finance development in Guangdong has any adverse impact on economic development. Data sources include the China Science and Technology Statistical Yearbook, China Energy Statistical Yearbook, China Financial Yearbook, China Industrial Statistical Yearbook, China Tertiary Industry Statistical Yearbook, statistical yearbooks from cities in Guangdong Province, environmental bulletins from each city, national economic and social development statistical bulletins, and authoritative websites of institutions such as the People's Bank of China.

3.2.2 Dependent Variables

The dependent variable is the growth rate of total factor productivity (TFPC) for 21 prefecture-level cities in Guangdong Province. Stochastic Frontier Analysis (SFA) is adopted to construct the model, as it allows comprehensive and stochastic sample selection while decomposing TFP into multiple components. The basic functional form is:

$$Y = f(X)e^{v-u} \quad (2)$$

Here, *Y* represents actual output, measured by "gross regional product" with 2000 as the base year. *X* denotes factor inputs (e.g., labor and capital). Capital (K_t) is calculated using the perpetual inventory method:

$$K_t = K_{t-1} \times (1 - 0.096) + m$$

where K_t is the capital stock in period *t*, K_0 is the base-year capital stock (2000), *m* represents fixed asset investment at constant prices, and the depreciation rate adopts 9.6% from Zhang, Wu & Zhang (2004). Labor (*L*) is measured by total employment, calculated by summing the number of urban unit employees and private individual employees. *v* is the random error term reflecting systemic inefficiency, and *u* is the technical inefficiency term. Following Battese & Coelli (1992), a translog stochastic frontier production function is specified:

$$\begin{aligned} \ln y_{it} = \ln f(K, L, t) = \beta_0 + \beta_K \ln K_{it} + \beta_L \ln L_{it} + \beta_t t + 0.5\beta_{KK}(\ln K_{it})^2 + 0.5\beta_{LL}(\ln L_{it})^2 \\ + \beta_{KL}(\ln K_{it})(\ln L_{it}) + \beta_{Kt}(\ln K_{it})t + \beta_{Lt}(\ln L_{it})t + \beta_{tt}t^2 + v_{it} - u_{it} \end{aligned} \quad (3)$$

Here, *Y* denotes economic output, *K* is capital, *L* is labor, subscripts i and t represent region and year, and β are estimated parameters. Following Kumbhakar & Lovell (2000), TFPC is decomposed into:

Technological Change (TC)

Technical Efficiency Change (TEC)

Scale Efficiency Change (SC)

Allocative Efficiency Change (AEC)

The aggregate output growth rate is expressed as:

$$GY = GA + GK + GL \tag{4}$$

where *GY* is the economic growth rate, *GA* is the TFP growth rate (TFPC), and *GK* and *GL* are the growth rates of capital and labor, respectively. TFPC is indirectly derived as:

$$GA = GY - GK - GL \tag{5}$$

Taking the derivative with respect to time *t* (subscripts omitted for simplicity):

$$TFPC = \frac{dlnY}{dY} \cdot \frac{dY}{dt} - \sum_j (\lambda_j \cdot \frac{dX_j}{dt}) \tag{6}$$

Expanding Equation (3) yields:

$$\frac{dlnY}{dY} \cdot \frac{dY}{dt} = \frac{\partial lnf(X,t)}{\partial t} + \sum_j \frac{\partial lnf(X,t)}{\partial(\ln X_j)} \cdot \frac{d(\ln X_j)}{dt} - \frac{\partial U}{\partial t} \tag{7}$$

$$\frac{dlnY}{dY} \cdot \frac{dY}{dt} - \sum_j \lambda_j \cdot \frac{d(\ln X_j)}{dt} = \frac{\partial lnY}{\partial t} - \frac{\partial U}{\partial t} + \sum_j \varepsilon_j \cdot \frac{d(\ln X_j)}{dt} - \sum_j \lambda_j \cdot \frac{d(\ln X_j)}{dt} \tag{8}$$

$$TFPC = \frac{\partial lnY}{\partial t} - \frac{\partial U}{\partial t} + \sum_j \varepsilon_j \cdot \dot{X}_j - \sum_j \frac{\varepsilon_j}{RTS} \cdot \dot{X}_j \tag{9}$$

$$TFPC = \frac{\partial lnY}{\partial t} - \frac{\partial U}{\partial t} + (RTS - 1) \sum_j \lambda_j \cdot \dot{X}_j \tag{10}$$

In Equation (10):

$$\lambda_j = \frac{\varepsilon_j}{RTS} \ ; \ \varepsilon_j = \frac{\partial \ln f(x_j)}{\partial (\ln x_j)} \ ; \ \dot{X}_j = \frac{d(\ln X_j)}{dt}$$

Here:

- $\frac{\partial lnY}{\partial t}$ represents TC (technological change).
- $\frac{\partial U}{\partial t}$ represents TEC (technical efficiency change).
- $(RTS - 1) \sum_j \lambda_j \cdot \dot{X}_j$ represents SC (scale efficiency change).

Thus, TFPC can be decomposed as follows:

(1)Technological Change (TC): TC is defined as the rate of change in the technological frontier after controlling for factor inputs. The formula is:

$$TC_{it} = \frac{\partial lnf(X,t)}{\partial t} = \beta_t + \beta_{Kt}(\ln K_{it}) + \beta_{Lt}(\ln L_{it}) + 2\beta_{tt}t \tag{11}$$

(2)Technical Efficiency Change (TEC): Following Leibenstein (1966), TEC is defined as the rate of change in production inefficiency over time. The formulas are:

$$TEC_{it} = \frac{\partial lnTE_{it}}{\partial t} = \frac{TE_{it} - TE_{it-1}}{TE_{it-1}} \tag{12}$$

$$TE_{it} = \frac{\partial U}{\partial t} = \exp(-u_{it}) \tag{13}$$

The technical inefficiency term u_{it} in Equation (13) is derived from the estimation of Equation (3).

(3)Scale Efficiency Change (SC): SC is defined as the rate of change in production efficiency due to scale effects. The formula is:

$$SC_{it} = (RTS - 1) \sum_j \lambda_j \dot{X}_j = (RTS_{it} - 1)(\lambda_{Kit} x_{Kit} + \lambda_{Lit} x_{Lit}) \tag{14}$$

Here:

RTS denotes returns to scale.

λ_j represents the output elasticity of input j relative to overall returns to scale.

ε_j represents the output elasticity of input j on the production frontier.

$\dot{X}_j$ denotes the growth rate of factor inputs, including x_K (capital) and x_L (labor).

(4)Allocative Efficiency Change (AEC): AEC is defined as the rate of change in resource allocation efficiency over time. The formula is:

$$AEC_{it} = \sum_j (\lambda_j - s_j) \dot{X}_j = (\lambda_{Kit} - s_{Kit}) x_{Kit} + (\lambda_{Lit} - s_{Lit}) x_{Lit} \tag{15}$$

Allocative efficiency is measured by the deviation between λ_j (output elasticity of input j) and s_j (cost share of input j). Optimal allocation occurs when $\lambda_j = s_j$. Here, s_K is the cost share of capital, and s_L is the cost share of labor, with $s_K + s_L = 1$.

The total factor productivity change (TFPC) is calculated as:

$$TFPC = TEC + TC + SC + AEC \tag{16}$$

Using Stata, TFPC and its components are estimated for Guangdong Province. Descriptive statistics are shown in Table 1.

Table 1. Descriptive Statistics of TFPC and Its Decomposition in Guangdong Province

Name	Sample Size	Min	Max	Mean	Std. Dev.	Median
SC	399	-3.326	0.552	-0.265	0.313	-0.228
TC	399	-0.099	0.143	0.004	0.040	0.003
TEC	399	-0.018	0.201	0.017	0.029	0.007
AEC	399	-0.186	0.384	-0.030	0.050	-0.027
TFPC	399	-2.969	0.762	-0.275	0.303	-0.259

Based on the calculation results, further exploration is conducted on the structure and structural changes of TFPC and its components in Guangdong Province, as shown in Figure 1.

Figure 1: Temporal trends of TFPC and its components in Guangdong province (2001–2019)

According to the dynamic changes of various decomposition indicators over time shown in Figure 1, the growth dynamics of TFPC and its components in Guangdong Province from 2001 to 2019 generally show a decreasing trend, indicating a loss of economic growth efficiency in recent years.

The technological progress (TC) was positive during the period from 2001 to 2011 but showed a slow downward trend. After 2012, it became negative, indicating that Guangdong's technological frontier output has been gradually declining, and the benefits from investments in technological innovation are diminishing. Technological efficiency improvement (TEC) has been positive, showing that recent improvements in technology efficiency have promoted TFPC. However, it has maintained a steady downward trend, approaching zero. Resource allocation efficiency improvement (AEC) also shows a downward trend, remaining negative since 2005. The declines in TEC and AEC suggest that recent factor inputs in Guangdong have not been converted into effective output. However, after 2015, although still negative, there was slight improvement, likely due to the increased influx of capital, talent, and high-tech, making the resource inputs more effective over time. The scale efficiency improvement (SC) has been negative for many years, indicating that changes in scale efficiency hinder TFPC, primarily due to environmental and error-related factors. The process can be divided into four stages: the first stage, from 2001 to 2004, saw a continuous decline in scale efficiency, possibly due to the extensive development problems arising as Guangdong's economy shifted from slow growth in the 1990s to rapid growth, with increasing economic openness and technological improvements in eastern and western Guangdong. The second stage, from 2004 to 2008, showed slight improvement, likely because Guangdong focused on supporting impoverished and mountainous areas and investing in infrastructure. The third stage, from 2008 to 2011, was impacted by the global financial crisis, causing a sharp decline followed by recovery, which affected scale efficiency. The fourth stage, from 2011 to 2019, saw a U-shaped trend in scale efficiency, first declining and then increasing. This may have been caused by increased investments in economic revitalization in Guangdong's eastern, western, and northern regions, leading to extensive development and a decrease in scale efficiency. However, the subsequent rapid growth in the number of legal entities, employees, and corporate assets, along with government investments in infrastructure, industrial park construction, urban expansion, and the large-scale application of high-tech, led to improvements in scale efficiency.

3.2.3 Independent Variable

This paper selects the green finance development level (GF) of 21 prefecture-level cities in Guangdong Province as the independent variable. The entropy method is employed, and Excel is used for raw data processing, measurement, and comprehensive evaluation. With the rising prominence of sustainable development topics, related literature has proliferated, and the evaluation system for green finance development levels has diversified. To ensure the accuracy and scientific rigor of the measurement results, this study prioritizes representative and quantifiable indicators for GF measurement. The specific indicators are listed in Table 2.

Table 2. Green finance development level measurement indicator system

Primary Indicator	Secondary Indicator	Indicator Nature	Calculation Method	Weight Coefficient
Green Finance Development Index	Green Credit	Positive	Environmental Project Credit Amount / Total Credit Amount	9.48%
	Green Investment	Positive	Environmental Pollution Control Investment / GDP	22.69%
	Green Insurance	Positive	Environmental Liability Insurance Revenue / Total Premium Income	9.45%
	Green Bonds	Positive	Green Bond Issuance Volume / Total Bond Issuance Volume	9.59%
	Green Support	Positive	Fiscal Environmental Protection Expenditure / General Fiscal Budget Expenditure	26.95%
	Green Funds	Positive	Green Fund Market Value / Total Fund Market Value	10.22%
	Green Equity	Positive	Carbon, Energy Use Rights, and Pollution Rights Trading / Total Equity Market Trading Volume	11.63%

The evaluation methods and indicator properties in the table above reference the works of Zhang et al. (2024). For green credit, some scholars use green credit balances or credit balances for high-energy-consuming and polluting industries (Hou et al., 2023). However, considering data availability and the representative nature of environmental project credit ratios, this paper adopts the ratio of environmental project credit to total credit. Green investment directly addresses environmental degradation and reflects regional efforts to promote green finance; thus, it is measured by the ratio of environmental pollution control investment to GDP. Green insurance is measured by the share of environmental liability insurance revenue in total premium income. Green bonds reflect capital market support for ecological development and are measured by the ratio of green bond issuance to total bond issuance. Green support, indicating governmental fiscal commitment to environmental protection, is measured by the ratio of fiscal environmental protection expenditure to general budget expenditure. Green funds and green equity are measured by their respective market shares, capturing financial market engagement in green initiatives.

To eliminate dimensional differences and standardize the data, dimensionless processing is applied before entropy method calculations. The steps are as follows:

(1)Comprehensive Evaluation Formula:

$$S_j = \sum_{j=1}^{m} w_j X_{ij}^* \tag{17}$$

Where, S_j represents the comprehensive evaluation value; w_j (0 ≤ w_j ≤ 1) represents the weight of each indicator; X_ij^* represents the evaluation object after dimensionless processing; i (i = 1, …, n) represents the i-th evaluated object, and j (j = 1, …, m) represents the value of the j-th indicator of the evaluated object.

(2)Dimensionless processing is applied to all the positive indicators in the indicator system, and the data is normalized to standardize all indicators, resulting in X_{ij}^*. The normalization process is as follows:

$$X_{ij}^* = \frac{X_{ij} - \min X_{ij}}{\max X_{ij} - \min X_{ij}} \tag{18}$$

(3)Translation processing is applied to ensure the internal patterns of the data remain intact after standardization, by adding 0.0001 to each value:

$$y_{ij} = X_{ij}^* + 0.0001 \tag{19}$$

(4)The proportion of the j-th indicator value of the i-th evaluated object to the total sum of the indicators for that object is calculated as follows:

$$P_{ij} = \frac{y_{ij}}{\sum_{j=1}^{m} y_{ij}} \tag{20}$$

(5)The entropy value for each indicator is calculated using the following formula:

$$P_{ij} = \frac{y_{ij}}{\sum_{j=1}^{m} y_{ij}} \tag{21}$$

Where $k = \frac{1}{\ln n}$, $k > 0$, and $0 \leq e_j \leq 1$.

(6)The information utility value, also known as the information divergence coefficient, is calculated to represent the data's information and volatility. The formula is:

$$d_j = 1 - e_j \tag{22}$$

The weight of each indicator is calculated using the formula:

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \tag{23}$$

Finally, the comprehensive score for each evaluated object is calculated using:

$$S_j = \sum_{i=1}^{m} (w_j \cdot X_{ij}^*) \tag{24}$$

Based on these calculations, the weight calculation results for each evaluated object in GF are summarized in Table 3.

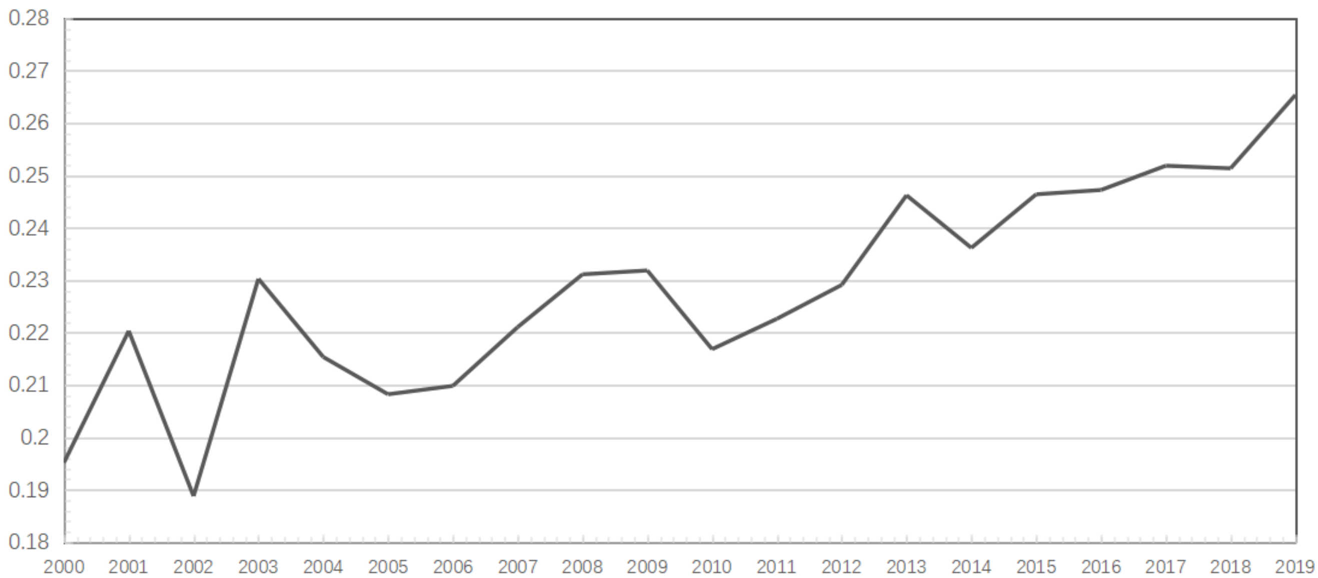
Table 3. The weight calculation results for various indicators in GF:

Indicator	**Entropy**	**Utility Value**	**Entropy Weight**
Green Credit	0.9793	0.0207	9.48%
Green Investment	0.9505	0.0495	22.69%
Green Insurance	0.9794	0.0206	9.45%
Green Bonds	0.9791	0.0209	9.59%
Green Support	0.9413	0.0587	26.95%
Green Funds	0.9777	0.0223	10.22%
Green Equity	0.9747	0.0253	11.63%

The results obtained using the entropy method show that Green Investment and Green Support have weights of 22.69% and 26.95%, respectively, indicating that these two are the main factors influencing the level of green financial development. Both indicators reflect the government's financial investment in environmental pollution control and protection, which directly promotes green development. Their significant share in the comprehensive evaluation indicates that the primary driving force for Guangdong’s green financial development from 2000 to 2019 came from government policies, demonstrating the province's commitment to implementing green development plans and its ongoing exploration of new green development models and pathways.

Based on the calculated results, further investigation into the dynamic changes of the GF comprehensive score over time is shown in Figure 2.

Figure 2. Dynamic temporal changes in the green finance development level in Guangdong province (2001–2019)



Based on the dynamic changes of GF over time shown in Figure 2, from 2000 to 2019, Guangdong's GF generally showed an increasing trend, with a slight decline in 2002 followed by a recovery in 2003. Afterward, there was a downward trend for two years. After 2005, it increased slowly in five-year cycles and slightly declined afterward. However, the overall trend still showed growth, indicating that the green financial development in Guangdong Province has achieved significant results under the implementation of green development plans in various prefecture-level cities across the province.

3.3 Control Variables

The data range for the control variables in this study is from 2000 to 2019 for the 21 prefecture-level cities in Guangdong Province. To control for the effects of other factors on regional total factor productivity, this study follows the approach of Liu & Zhu (2024), ultimately adopting the following indicators: (1) Economic Development: The logarithm of the per capita GDP adjusted for inflation is used as a measure, where the ratio of the actual GDP in 2000 to the total population at the end of the year serves to control the nonlinear impact of economic development on total factor productivity; (2) Government Intervention: Measured by the ratio of fiscal expenditure to GDP; (3) Environmental Regulation: Measured by the ratio of total investment in environmental pollution control to GDP; (4) Urban Scale: Measured by taking the logarithm of the registered urban population; (5) Unemployment Rate: Measured by the urban registered unemployment rate; (6) Industrial Structure: Measured by the proportion of the value added by the secondary and tertiary industries to GDP; (7) Education Expenditure Level: Measured by the ratio of education expenditure to the local government’s general public budget expenditure. The raw data for each variable come from city statistical yearbooks, publications by statistical bureaus, work reports of various cities, and the national economic and social development statistical bulletins of each city. For a small amount of missing data, linear interpolation was used to fill the gaps.

Table 4. Definition of Key Variables and Descriptive Statistics

Indicator	Variable Name	Variable Abbreviation	Sample Size	Mean	Standard Deviation	Min	Max
Dependent Variables	Total Factor Productivity	TFPC	399	-0.275	0.303	-2.969	0.762
	Technological Progress	TC	399	0.004	0.04	-0.099	0.143
	Technological Efficiency Progress	TEC	399	0.017	0.029	-0.018	0.201
	Scale Efficiency Progress	SC	399	-0.265	0.313	-3.326	0.552
	Allocation Efficiency Progress	AEC	399	-0.03	0.05	-0.186	0.384
Independent Variable	Green Finance Development Level	GF	399	0.23	0.07	0.047	0.444
Control Variables	Economic Development	pgdp	399	6.585	9.105	0.3	45.621
	Government Intervention	gov	399	0.129	0.063	0.048	0.399
	Environmental Regulation	env	399	0.035	0.029	0.002	0.239
	Urban Scale	scale	399	5.875	0.529	4.33	6.861
	Unemployment Rate	ump	399	2.573	0.423	0.5	3.76
	Industrial Structure	isT	399	0.884	0.088	0.59	1.068
	Education Expenditure Level	eel	399	0.21	0.053	0.014	0.477

4. Empirical Results and Analysis

4.1 Baseline Regression Results

As shown in Table 5, control variables are sequentially added from columns (1) to (8), ultimately establishing the baseline model estimation results. The parameter estimates reveal that after controlling all variables, the GF's coefficient on TFPC is statistically significant and negative at the 1% confidence level, indicating that green finance development negatively impacts total factor productivity, which aligns with hypothesis H1b's theoretical predictions.

Table 5. Baseline regression of green finance development on total factor productivity

Variable	TFPC							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
GF	0.025	-0.063	-0.185***	-0.187***	-0.181***	-0.172***	-0.173***	-0.167***
	(0.45)	(-1.14)	(-2.79)	(-2.82)	(-2.81)	(-2.67)	(-2.70)	(-2.60)
pgdp		0.784***	0.706***	0.870***	1.413***	1.268***	1.226***	1.202***
		(5.30)	(4.77)	(5.20)	(6.96)	(5.83)	(5.65)	(5.54)
env			0.354***	0.366***	0.365***	0.366***	0.411***	0.386***
			(3.20)	(3.32)	(3.41)	(3.42)	(3.80)	(3.55)
gov				0.366***	0.365***	0.366***	0.411***	0.386***
				(3.32)	(3.41)	(3.42)	(3.80)	(3.55)

Variable	TFPC							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
scale					-1.571***	-1.497***	-1.463***	-1.490***
					(-4.48)	(-4.25)	(-4.18)	(-4.27)
ump						0.138*	0.134*	0.156**
						(1.83)	(1.79)	(2.07)
isT							0.199**	0.232**
							(2.18)	(2.50)
eel								0.133*
								(1.86)
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.135	0.198	0.220	0.229	0.271	0.277	0.287	0.294
Sample size	399	399	399	399	399	399	399	399

Note: *, **, and *** indicate that the estimated coefficients are significant at the 10%, 5%, and 1% significance levels, respectively; same table below.

Combining the results of the simple regression estimation, it can be seen that GF does not show a facilitating effect on TFPC, but instead has a certain degree of inhibiting effect. For this reason, the causes of this problem will be further explored in this paper.

4.2 Mechanism Tests

In order to better explore the mechanism of action of the negative effect of GF on TFPC, TFPC was decomposed and regression estimation was performed for each component separately to analyze the mechanism of the effect of GF on TC, TEC, SC, and AEC, respectively, and the results are shown in Table 6.

Table 6. Regression estimation results of green financial development on each decomposition component of total factor productivity

Variable	TC		TEC		SC		AEC	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
GF	0.242***	0.108***	-0.092**	-0.142***	-0.027	-0.196***	0.175***	0.207***
	(8.43)	(4.59)	(-2.14)	(-2.80)	(-0.49)	(-2.93)	(3.48)	(3.28)
pgdp		1.135***		-0.431**		1.016***		0.261
		(14.25)		(-2.51)		(4.49)		(1.22)
gov		0.003		0.016		0.420***		0.009
		(0.06)		(0.14)		(2.84)		(0.07)
env		-0.012		0.332***		0.379***		-0.215**
		(-0.31)		(3.85)		(3.34)		(-2.00)
scale		0.079		-0.678**		-1.385***		-0.036
		(0.61)		(-2.45)		(-3.80)		(-0.10)

Variable	TC		TEC		SC		AEC	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ump		0.022		0.310***		0.113		0.045
		(0.80)		(5.17)		(1.43)		(0.60)
isT		-0.099***		-0.090		0.312***		-0.410***
		(-2.89)		(-1.22)		(3.22)		(-4.48)
eel		0.028		-0.139**		0.153**		-0.094
		(1.05)		(-2.44)		(2.05)		(-1.33)
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.712	0.886	0.506	0.591	0.073	0.209	0.289	0.335
Sample size	399	399	399	399	399	399	399	399

According to the estimation results in Table 6, columns (1) and (2) show that the estimated coefficient of GF on TC is 0.108, which is statistically significant and positive at the 1% confidence level. This indicates that the development of green finance has promoted technological progress in Guangdong Province, consistent with hypothesis H2a. This suggests that green finance development has successfully guided capital and resources to the construction of green-related fields in the region, improved the availability of funds for enterprises, and driven corporate investment in green technology through related funding and policies, thereby stimulating regional technological innovation and ultimately enhancing overall technological progress in the region.

From columns (3) and (4), the estimated coefficient of GF on TEC is -0.142, which is statistically significant and negative at the 1% confidence level. This demonstrates that green finance development has a negative impact on technical efficiency in Guangdong Province, aligning with hypothesis H3b. A possible explanation is that green finance development has redirected capital and resources to energy-saving and environmentally friendly enterprises, leaving non-environmentally friendly enterprises—particularly small and medium-sized ones—struggling to obtain sufficient funding. Consequently, these enterprises face greater difficulties in achieving and acquiring innovative technologies, while simultaneously experiencing increased management costs, R&D expenses, and risks. Moreover, under green development pressures, non-environmentally friendly enterprises are more susceptible to external financing constraints, leading to declining technical efficiency and ultimately affecting regional technical efficiency improvements.

Columns (5) and (6) reveal that the estimated coefficient of GF on SC is negative and becomes statistically significant at the 1% confidence level after controlling for other variables. This indicates that green finance development has a significant negative impact on scale efficiency in Guangdong Province, supporting hypothesis H4b. The rapid advancement of green finance development may have channeled resources to already saturated enterprises, causing them to deviate from optimal scales. Simultaneously, non-environmentally friendly enterprises receive less support and experience lower production efficiency. Given Guangdong's historical context of extensive economic expansion and massive influx of talent, enterprises, and resources, green finance development may have exacerbated these issues.

Columns (7) and (8) show that the estimated coefficient of GF on AEC is statistically significant and positive at the 1% confidence level, indicating that green finance development has positively influenced resource allocation efficiency in Guangdong Province, consistent with hypothesis H5a. This demonstrates that green finance development has redirected capital and resources from low-efficiency enterprises to high-efficiency ones, and from polluting enterprises to non-polluting ones. These resource reallocations have generated positive effects on total factor productivity in the region.

4.3 Robustness Test

This study conducted robustness checks by replacing the dimensionless normalization method in the GF indicator measurement from the normalization approach to standardization, recalculating GF as GF2, and re-estimating the regression model. Table 7 results demonstrate that GF after the measurement method replacement still exerts a statistically significant negative impact on TFPC, further verifying the reliability of hypothesis H1b.

Table 7. Robustness test results

Variable	TFPC							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
GF2	0.036	-0.060	-0.206***	-0.206***	-0.201***	-0.192***	-0.192***	-0.185***
	(0.64)	(-1.05)	(-2.88)	(-2.90)	(-2.91)	(-2.78)	(-2.79)	(-2.69)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.135	0.197	0.221	0.230	0.272	0.279	0.288	0.295
Sample size	399	399	399	399	399	399	399	399

4.4 Endogeneity Test

Despite rigorous efforts to control confounding factors, persistent risks of omitted variable bias and potential reverse causality result in endogeneity concerns. This study employs an instrumental variable (IV) approach, drawing on methodological frameworks from Guo, Zhang & Liu (2022), by utilizing Internet penetration rate (iba) operationalized through broadband subscriber density. Given the presence of serial correlation in total factor productivity measurements, we implement a system GMM dynamic panel model with dual fixed effects to address this methodological challenge and verify our baseline findings. The regression outputs presented in Table 8 reveal significantly negative coefficients for GF, mirroring both magnitude and significance from our baseline specifications, demonstrating that green finance development's adverse impact on regional productivity remains statistically robust.

Table 8. SYS-GMM estimation results

Variable	Phase 1 results GF	Phase 2 results TFPC
Iba	0.262***	
	(2.98)	
GF		-0.933**
		(-2.05)
Control variables	Yes	Yes
Time fixed effects	Yes	Yes
Individual fixed effects	Yes	Yes
R^2	0.395	0.379
Sample size	399	399

5. Conclusions and Policy Implications

5.1 Conclusions

To advance the coordinated development of green finance and the economy in Guangdong Province, this paper employs panel data from 21 prefecture-level cities (2000–2019) to empirically analyze the mechanisms through which green finance affects regional total factor productivity (TFP), with a focus on technological progress, technical efficiency, scale efficiency, and allocative efficiency. The findings are as follows: (1) Green finance development in Guangdong has a significant negative impact on regional TFP growth. This conclusion remains robust after addressing endogeneity concerns and recalculating the green finance indices. (2) Mechanism analysis reveals that while green finance promotes technological progress and improves resource allocation efficiency, it simultaneously hinders improvements in technical and scale efficiency. The net effect on regional TFP is negative. This indicates that the rapid advancement of green finance exerts a complex influence on TFP. (3) In terms of the internal impact structure, the suppression of TFP growth by green finance is primarily attributable to its negative effects on regional technical and scale efficiency.

5.2 Policy Recommendations

First, policies should be tailored to different types of enterprises. Priority must be given to transforming traditional, non-energy-efficient, and environmentally unfriendly enterprises by imposing stricter penalties on underperformers. For companies with opaque or problematic environmental disclosures, appropriate sanctions should be applied, and oversight of their green financial assets must be strengthened to enhance the quality and sustainability of regional green finance. Increasing the strength and coverage of green policy support, particularly by lowering green credit interest rates, will reduce financing, transformation, and R&D costs for traditional firms. This will boost their willingness to innovate and transform, stimulate regional technological innovation, improve the liquidity and allocation efficiency of green financial resources across traditional and green industries, and ultimately promote industrial upgrading and regional scale efficiency.

Second, green finance policies should be regionalized. Given the varying levels of economic development across Guangdong, greater supervision over fund and resource allocation should be exercised in less developed areas. This will ensure that even amid unavoidable rough economic expansion, enterprises use resources more prudently and efficiently. At the same time, differentiated green economic development programs should be designed for different regions to ensure effective implementation and avoid a "one-size-fits-all" approach. By deeply understanding local conditions and needs, we can formulate green finance policies that are better aligned with reality. Moreover, inter-regional cooperation in green finance should be strengthened, encouraging developed areas to collaborate with less developed ones. Establishing a cross-regional cooperation mechanism involving financial institutions, enterprises, and governments can facilitate technology transfer and experience sharing, thereby raising regional technical efficiency and mitigating the diminishing efficiency returns that often accompany economic expansion.

Third, policies should target the specific pathways through which green finance affects total factor productivity. Programs supporting green technological innovation should be established to help enterprises secure more funding for adopting high-efficiency technologies, upgrading low efficiency processes, and developing green technologies and products. Financial institutions should also be encouraged to innovate in green financial products. These measures will elevate the region's overall technological level, amplify the role of technological progress in boosting productivity, and improve technological efficiency.

Additionally, green support and regulation should be enhanced, information transparency improved, and enterprises encouraged to allocate resources more rationally. This will increase capital and resource allocation efficiency across industries and magnify its positive impact on total factor productivity. By refining the green finance evaluation system to assess and rank the practices of institutions and enterprises, we can incentivize continuous improvement in the quality and scale of green business and bolster policy support for green transformation and production scaling. This will help low efficiency enterprises optimize their structure, reduce costs, and improve technological and allocation efficiencies. Simultaneously, the green finance risk management system should be upgraded to accurately assess project level environmental risks, enabling financial institutions to correctly identify and price such risks. This will mitigate the potential negative impact of risks on technical efficiency and help maintain regional technical efficiency at a relatively stable level. Finally, public and corporate environmental awareness should be raised through media campaigns, education, and training. The government should also refine green planning and avoid excessive economic expansion to achieve sustainable gains in scale efficiency.

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Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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