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Driving economic sustainability in China: the role of renewable energy, green finance, and government intervention

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China is committed to achieving carbon neutrality by 2060, highlighting the importance of identifying key factors that promote sustainable economic development. Based on endogenous growth and energy-growth nexus theories, this study investigates how renewable energy, green technology innovation, green finance and government intervention affect Green Total Factor Productivity (GTFP) in 30 Chinese provinces from 2010 to 2022. To obtain robust and reliable estimation results, this study employs Generalized Least Squares (GLS), Driscoll-Kraay standard errors (D-K), and the two-step systematic Generalized Method of Moments (GMM) method for empirical analysis. The findings demonstrate that renewable energy, green finance, and green technology innovation significantly improve GTFP, with coefficients of 0.054, 2.153, and 0.091, respectively, all statistically significant at the 1% level. Notably, the impact of green finance on GTFP indicates significant geographical disparities, with the central region having the strongest effect (coefficient = 1.258). Further, the analysis indicates that GOV and GTFP have a U-shaped relationship. Moreover, the moderation effect of green finance and government intervention with green technology innovation is found to exert a positive and significant effect on GTFP, with interaction coefficients of 0.089 and 0.046, respectively.

KEYWORDS

government intervention, green finance, green total factor productivity, renewable energy, sustainable development

1 Introduction

China faces the critical challenge of promoting economic transformation and pursuing sustainable economic development amidst mounting environmental pressures. The traditional growth model is characterized by high energy intensity and severe dependence on fossil fuels, generating large environmental externalities, threatening long-term productivity and development quality. Green total factor productivity (GTFP) growth, which inherently embodies energy conservation and emission reduction, is increasingly becoming a key driver of high-quality economic development. GTFP, as a key metric for measuring sustainable economic development, reflects the objective of maximizing economic output while limiting resource depletion and adverse environmental impacts (Jiakui et al., 2023; Yao and Xi, 2023). The Chinese government has developed a strategy for carbon peaking and neutrality. Improving GTFP is essential for China's transition to a sustainable economic model and achieving its carbon peaking and neutrality targets, which also align with the intrinsic objectives of Sustainable Development Goal (SDG) 8.

Energy structure transformation plays a crucial role in improving GTFP and directly affects energy efficiency and environmental performance (Lei and Xu, 2023; Li Q. et al., 2024). However, China's economic growth has long relied heavily on fossil fuels, yet this development model has led to substantial environmental degradation (Abbasi et al., 2022). Therefore, attaining sustainable economic growth and meeting the sustainable development goals depend on facilitating the shift in the energy structure from fossil fuels to renewable energy. The development of renewable energy is highly dependent on technological innovation, and its effectiveness is closely related to the effectiveness of green technology innovation. Fully applying technological innovations in the energy sector can effectively improve energy efficiency and reduce environmental externalities (Behera P. et al., 2024; Erdogan et al., 2023). However, both the rapid transition to renewable energy and the innovative breakthroughs in green technologies are capital-intensive activities that require substantial financial support.

Green finance (GF) is defined as financial instruments and investment activities orientated towards environmental sustainability goals (Yu et al., 2026), which effectively promotes the improvement of GTFP by guiding funds to clean energy projects and green technology innovation. Meanwhile, government intervention (GOV) offers essential institutional support via regulation, subsidies and policy coordination, promoting efficiency improvements, technical advancement, and industrial upgrading, hence facilitating a boost in GTFP (Uzar, 2020). REN, GTI, GF, and GOV are all interconnected, forming a holistic framework. Studies on green synergistic development has highlighted their interactions and synergistic impacts on green productivity (Yin et al., 2022; Zameer et al., 2020).

Despite increasing academic studies on the factors impacting GTFP (Dai et al., 2025; Guo et al., 2025; Wang et al., 2026), there is still a significant gap in understanding the integrated mechanisms underlying China's sustainable economic development. First, most of the existing studies analyze REN, GTI, GF and GOV separately, lacking a unified analysis framework to show their synergistic and interactive effects on GTFP. Secondly, the possible nonlinear relationship among REN, GOV and GTFP in the actual scene of China, especially by incorporating the squared term into the model, has not been fully studied. Finally, the influence of interaction terms (GF × GTI, GOV × GTI) on GTFP has not been comprehensively investigated.

The purpose of this study is to fill these gaps and specifically answer three research questions as follows:

RQ1: What are the specific effects of REN, GTI, GF, and GOV on China's GTFP?

RQ2: Is there a nonlinear relationship among REN, GOV and GTFP?

RQ3: Do GF and GOV play a moderating role in the link between GTI and GTFP?

This study contributes to three key aspects. Firstly, it establishes a unified analytical framework incorporating REN, GF, GTI, and GOV, experimentally investigating the synergistic mechanisms through which these factors affect GTFP. Secondly, this study extends existing research by revealing nonlinear and interaction mechanisms underlying China's green transition. The findings show a U-shaped relationship between GOV and GTFP and demonstrate that the productivity impact of GTI is conditionally moderated by GF and GOV, highlighting the roles of policy intensity and financial development. Thirdly, the findings provide target policy recommendations for China to take advantage of these synergistic effects, thus facilitating the enhancement of GTFP and promoting the achievement of the multiple Sustainable Development Goals (SDGs), including SDGs 7, 8, 9, 12 and 13.

Furthermore, this study also uses GLS, Driscoll-Kraay and two-step system GMM to solve the problems of heteroscedasticity, autocorrelation, cross-section correlation and potential endogeneity, and enhance the robustness and credibility of the empirical results. At the same time, Dumitrescu-Hurlin panel causality test method is used to analyze the predictive correlation and causal direction between core variables.

The empirical results show that REN, GF and GTI can promote the promotion of GTFP in 30 provinces of China, and GOV and GTFP exhibit a U-shaped relationship. In addition, the interaction between GF and GTI, GOV and GTI both have a positive effect on GTFP. Based on these conclusions, this study suggests that policymakers should combine regulatory constraints and market incentives to promote GTFP and help achieve sustainable development goals.

2 Literature review

In the twenty-first century, balancing environmental protection with sustainable economic growth has become a common global challenge. The existing literature has extensively discussed the influence of REN, GTI, GF and GOV on GTFP. Therefore, this study combed the existing related literature and identified the research gaps.

2.1 Renewable energy and green total factor productivity

The relationship between REN and GTFP has already been studied extensively. Most studies believe that REN can have a positive impact on GTFP by improving energy efficiency and reducing negative environmental externalities (Huang H. et al., 2025; Sun et al., 2025). Studies from developed countries and emerging economies have shown that replacing fossil fuels with renewable energy can improve production efficiency and reduce carbon emissions, thus promoting sustainable economic development (Bashir et al., 2024; Sohag et al., 2021). Some studies also point out that advanced technology, human capital and investment in R&D will significantly affect macroeconomic output (Amin et al., 2025; Šlander-Wostner et al., 2025). However, existing studies have not reached completely consistent conclusions. For example, Tugcu and Tiwari (2016) found that between 1992 and 2012, the development of renewable energy in BRICS countries did not have a significant impact on total factor productivity growth. The disparity could be due to the extent of data coverage, testing techniques, or environmental context. A few studies have also found a non-linear relationship between REN and GTFP (Xie et al., 2021).

Xie et al. (2021) found that there is a threshold effect in the relationship between green finance and green total factor productivity, which becomes significant only when green finance development exceeds a certain threshold. It is worth noting that, in the Chinese context, the actual effectiveness of renewable energy applications is also affected by regional transition models and policy changes (Wu et al., 2025a). Despite the widespread attention this type of research has received, there are still disagreements regarding its empirical results. Against the backdrop of energy transition, this study focuses on the impact of REN on GTFP, as well as its potential nonlinear characteristics.

2.2 Green technology innovations and green total factor productivity

Enhancing GTFP has become crucial for attaining high-quality growth as China's economy enters a new phase, with GTI playing a key part in this process (Shen et al., 2022). Prior empirical studies have highlighted GTI's ability to boost productivity, primarily through improvements in efficiency and regulation-induced innovation output (Zhao et al., 2025). Government digitization and green financing strengthen the effectiveness of such technologies by improving governance capability and resource allocation efficiency (Huang X. et al., 2025; Zeng et al., 2025). On the one hand, GTI enhances energy efficiency and adopting cleaner technologies to lessen the reliance on traditional inputs that create negative environmental externalities (Wang J. et al., 2023). Additionally, stricter environmental regulations promote green innovation opportunities, which lead to green productivity-enhancing effects (Feng et al., 2017). Further, there is evidence in the literature that the link between GTI and GTFP has a conditional, nonlinear character. For instance, Yan et al. (2020) found that renewable energy technological innovation contributes to green productivity only after the regional income level reaches a certain threshold. Likewise, following the "appropriateness" theory and the "productivity paradox," Kong et al. (2015) argued that when technological innovation is inappropriate for the country's development stage or the structure of factor endowments, its productivity-enhancing impact on GTFP will possibly be very poor. While GTI is considered an essential driver for GTFP, its real effectiveness is affected by the institutional environment in which it operates. However, in context with China's economic transition, whether the process by which GTI influences GTFP is influenced by finance and government intervention has not yet been further examined.

2.3 Green finance and green total factor productivity

GF, by reallocating capital to environmentally friendly activities, has become an important mechanism for promoting sustainable economic development. Most macro-level empirical data demonstrates this positive relationship. For instance, Meng et al. (2024) and Lee and Lee (2022) illustrated that GF greatly boosts GTFP through facilitating technological innovation and upgrading the energy structure, with stronger effects in supportive economic and institutional settings. However, the empirical conclusions at the micro level are inconsistent. For example, Piao et al. (2025) discovered that green financial policies adversely effect on GTFP in highly polluting industries, because such policies will aggravate the financing constraints of enterprises and increase the cost of transformation. The relationship between GF and GTFP has nonlinear characteristics besides the linear effect. Shi and Shi (2022) found that there is a threshold effect in the relationship between GF and GTFP, which becomes significant only when green finance development exceeds a certain threshold. The effects of GF on the green economy differ significantly due to institutional and market environments, including fluctuations in carbon prices and economic uncertainty (Wang K. H. et al., 2023; Wu et al., 2025b). The present body of research primarily examines the influence of GF on GTFP from macro or micro perspectives. The synergistic effects of GF, REN, GTI, and GOV on GTFP, along with their regional heterogeneity, and the moderating role of GF in the influence of GTI on GTFP, are still relatively unexplored at the meso-level (provincial).

2.4 Government intervention and green total factor productivity

Studies already conducted indicate that through regulation, subsidies, and policy coordination, the government, acting as the "visible hand," greatly raises GTFP (Zhang Z. et al., 2024; Zhou D. et al., 2023). Zhao and Ying (2023) pointed out that the government can promote the transformation of energy structure and improve GTFP by formulating energy policies. Under the "dual carbon" target, the government can provide funds to green enterprises to help them control pollution and reduce emissions (Ma et al., 2025), while also promoting green innovation through subsidies (Ren and Lv, 2014). However, further study has highlighted that excessive or improper government involvement may distort market incentives and resource allocation, thereby reducing GTFP. For example, Wang and Luo (2018) found that government subsidies may give rise to overcapacity and overinvestment in certain industries. Similarly, according to Brandt et al. (2013), local governments are prone to misallocating resources to meet short-term economic growth targets, which distorts factor market prices and eventually makes it more difficult to promote GTFP. Despite the lack of consensus in prior research findings, the nonlinear impact of GOV on GTFP, along with its moderating role in the process through which GTI influences GTFP, has yet to be fully investigated using provincial-level data.

3 Theoretical framework and hypothesis development

This study employs the Cobb-Douglas production function, which is widely utilized in economics. This function highlights how changes in labor and capital inputs, which are vital elements of production, correlate to changes in economic output (Sethi et al., 2024). The Energy-Growth Nexus Theory proposes that energy plays a critical role in determining economic performance. Compared with fossil fuels, REN has obvious advantages in improving energy efficiency and reducing negative environmental externalities, so it can effectively promote productivity improvement and sustainable growth (Algarni et al., 2023). Moreover, endogenous growth theory emphasizes that technological progress is the core driving force to promote the continuous improvement of productivity. As a key component of innovation, GTI facilitates the green transformation and upgrading of enterprises, increases factor utilization's effectiveness, reduces environmental costs, and serves as a key driver of sustainable economic development (Cheng et al., 2024).

GF can solve the financing issues of green projects and environmental protection enterprises, guide the funds to flow to green low-carbon technologies and clean energy industries, and then strengthen the promotion of technology application to enhance GTFP (Qing et al., 2024). At the same time, the institutional environment, especially the role of the government, will also profoundly influence the level of green productivity. Porter and Linde (1995) argued that appropriate policies can stimulate the R&D enthusiasm of enterprises, correct the market failure caused by environmental problems, and guide the economic structure to green transformation. Thus, GTFP will be influenced by renewable energy consumption, government policies, green technology innovation, and green financial development. Therefore, it is necessary to combine relevant theories and research hypotheses to systematically analyze the comprehensive mechanism of these factors affecting GTFP.

3.1 Hypothesis of the study

Promoting sustainable development requires the coordinated advancement of economic growth and environmental protection. GTFP has therefore been widely adopted, particularly in China, to evaluate the level of high-quality economic development and ecological efficiency. Since GTFP inherently integrates these two dimensions, identifying its key determinants is crucial. Renewable energy transition plays a key role in promoting economic and environmental sustainability. Research indicates that REN increases energy efficiency and reduces fossil fuel use and environmental damage (Zhao et al., 2021). The energy-growth nexus theory also suggests that energy use and economic growth are closely connected. In this framework, REN contributes to growth and reduces ecological pressure, supporting green and sustainable development (Wang et al., 2024). Therefore, REN is expected to positively affect GTFP, as proposed in Hypothesis 1, i.e., $\frac{\beta GTFP_{it}}{\beta REN_{it}} > 0$.

Endogenous growth theory highlights technological innovation as a primary internal driver of economic growth. The development of clean energy heavily depends on technological advancement, with GTI playing a central role (Jiakui et al., 2023). Previous studies show GTI can enhance energy efficiency, alleviate emission reduction pressures, improve the utilization efficiency of renewable energy, and promote green economic growth (Wang J. et al., 2023). It is evident that GTI primarily contributes to sustainable economic development by enhancing green production efficiency. Thus, GTI is assumed to exert a beneficial influence on GTFP, i.e., $\frac{\beta GTFP_{it}}{\beta GTI_{it}} > 0$, as stated in hypothesis 2.

Similarly, GF enhances GTFP primarily through capital allocation and risk aversion effects. On the one hand, GF directs productive resources toward more environmentally efficient sectors. Guided by the ESG (Environmental, Social, and Governance) principles, green finance theory indicates that the financial institutions reallocate funds from high-pollution and energy-intensive industries to green technology and clean energy projects through financial instruments (Xu et al., 2023). By alleviating financing constraints on green investments and optimizing resource allocation through market-based signals, GF contributes to the improvement of GTFP (Behera B. et al., 2024). On the other hand, GF internalizes environmental risks through risk avoidance mechanisms, thereby incentivizing economic entities to accelerate the green transition. Green finance instruments, such as green credit standards, increase financing costs and raise compliance costs for pollution-intensive firms, driving them to internalize environmental externalities and accelerate innovation of green technology (Zhang et al., 2022). This risk-pricing mechanism boosts corporate incentives for green investment, improves resource allocation, and fosters green technical innovation, ultimately leading to the enhancement of GTFP (Jiakui et al., 2023; Lee and Lee, 2022). Based on these theoretical foundations, this study hypothesizes that GF has a positive impact on GTFP, i.e., $\frac{\beta GTFP_{it}}{\beta GF_{it}} > 0$, as stated in hypothesis 3.

In addition, the government affects green production efficiency via regulation and market incentives. Institutional distortions will result from inadequate governance and improper policy design when government involvement is limited, such as resource mismatch and crowding out market activity space (Tang and Qin, 2022). In this situation, government actions often replace the market regulation function, weaken the role of price signals, and direct resources such as capital and labor to areas with low efficiency. At the same time, subsidy-based support will also crowd out private investment and reduce enterprises' initiative for independent innovation (Aragie and Pauw, 2019). Therefore, the GOV in this case is not a supplement to the market, but a substitute for the market, which will hinder the promotion of GTFP.

When the government intervenes more, its role will change. Government behavior is no longer replacing the market but is beginning to help correct its failure. For example, environmental taxes and carbon pricing incentivize enterprises to consider environmental costs when making operational and production decisions. In addition, technical standards and R&D subsidies facilitate companies adopting and spreading green technologies. Together, these initiatives increase energy efficiency while promoting the use of renewable energy sources, which leads to higher green total factor productivity. As illustrated in Figure 1. Thus, hypothesis 4, there is a U-shaped relationship between GOV and GTFP.

Moreover, GF reduces financing costs and creates an advantageous policy environment that encourages investment in R&D, especially when combined with moderate government intervention, thereby fostering GTI (Akhtaruzzaman et al., 2025; Xu and Lin, 2024), contributing to sustainable development. Given that the interaction effects of GF and GOV with GTI are estimated to promote the improvement of GTFP, the interaction terms' coefficients are assumed to be positive, i.e., $\frac{\beta GTFP_{it}}{\beta GF \times GTI_{it}} > 0$, and $\frac{\beta GTFP_{it}}{\beta GOV \times GTI_{it}} > 0$, in hypothesis 5 and hypothesis 6, respectively. A diagram of the theoretical framework and hypotheses is shown in Figure 2.

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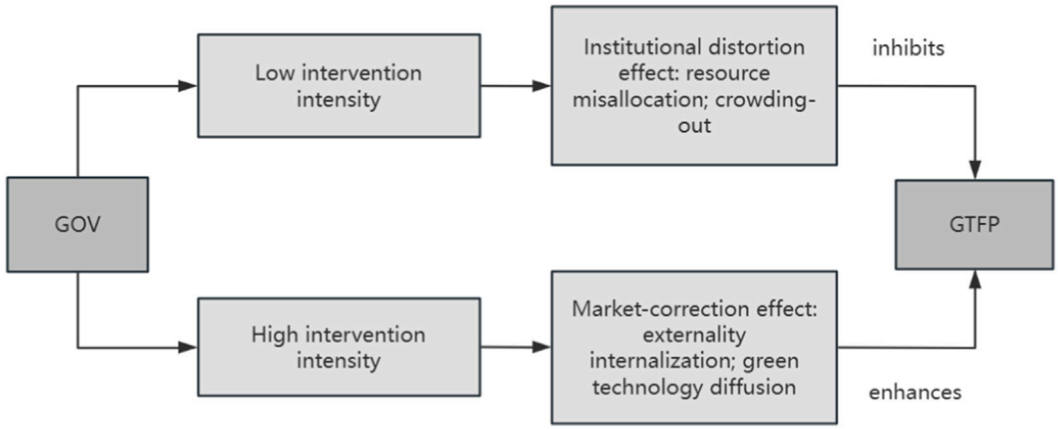

FIGURE 1
U-Shaped Relationship between government intervention and green total factor productivity. Note: GOV denotes government intervention, and GTFP denotes green total factor productivity. Source: Authors' illustrations are based on the theoretical analysis.

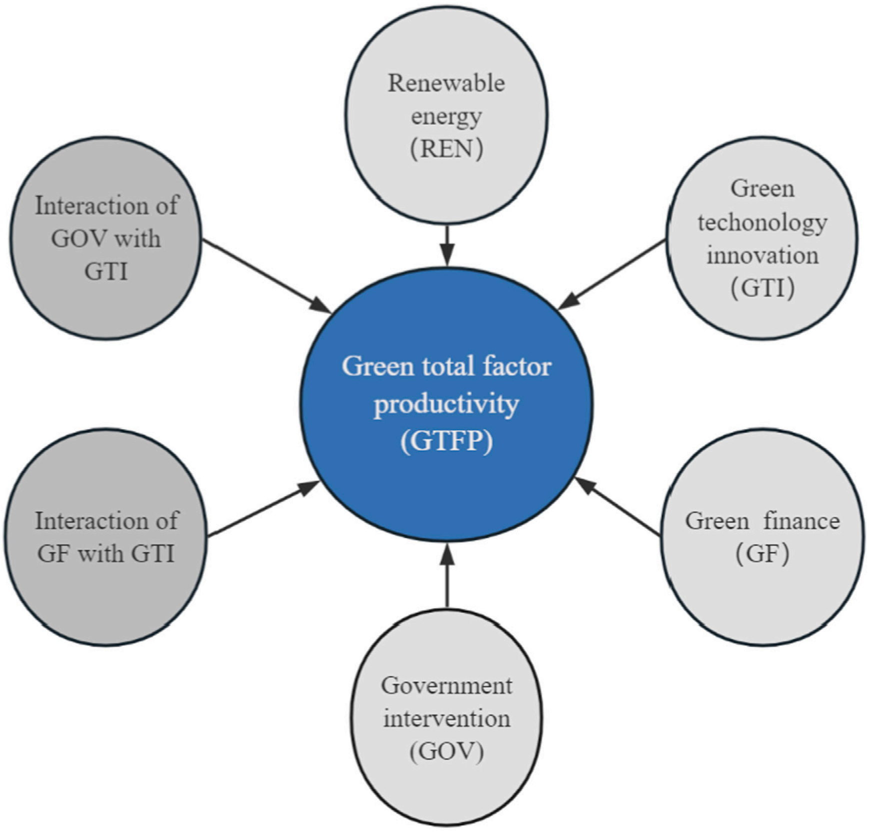

FIGURE 2
A theoretical framework exploring both the direct and interactive influences of explanatory variables across different hypotheses. Source: Authors' own work.

4 Data and methodology

4.1 Model specification

For empirical analysis, this study followed Sethi et al. (2024) and formed the baseline equation, which is illustrated in Equation 1.

$$\begin{aligned}\operatorname{Ln} GTFP_{it} &= \alpha + \beta_1 \ln REN_{it} + \beta_2 \ln GF_{it} + \beta_3 \ln GTI_{it} \\ &+ \beta_4 \ln GOV_{it} + \beta_5 Z_{it} + \mu_{it}\end{aligned} \tag{1}$$

Where in Equation 1 the subscripts i and t represent the province and year, respectively. $GTFP_{it}$ is the dependent variable, measuring green total factor productivity, REN_{it}, GF_{it}, GTI_{it}, and GOV_{it} are independent variables, denoting renewable energy consumption, green finance, green technology innovation, and government intervention, respectively. Z_{it} denotes the vector of control variables, including transportation infrastructure, trade openness, and industrial structure upgrading, and μ_{it} denotes the residual term.

Furthermore, to examine the potential non-linear effects of REN and GOV on GTFP, Equation 1 is extended by incorporating the squared terms of REN and GOV, as presented in Equations 2, 3, respectively.

$$\begin{aligned}\operatorname{Ln} GTFP_{it} &= \theta + \gamma_1 \ln REN_{it} + \gamma_2 \ln GF_{it} + \gamma_3 \ln GTI_{it} \\ &+ \gamma_4 (\ln REN_{it})^2 + \gamma_5 \ln GOV_{it} + \gamma_6 Z_{it} + \mu_{it}\end{aligned} \tag{2}$$

$$\begin{aligned}\operatorname{Ln} GTFP_{it} &= \vartheta + \delta_1 \ln REN_{it} + \delta_2 \ln GF_{it} + \delta_3 \ln GTI_{it} \\ &+ \delta_4 \ln GOV_{it} + \delta_5 (\ln GOV_{it})^2 + \delta_6 Z_{it} + \mu_{it}\end{aligned} \tag{3}$$

Where $(\ln REN_{it})^2$ and $(\ln GOV_{it})^2$ represent the squared term of renewable energy consumption and government intervention in Equations 2, 3, respectively. The remaining variable symbols' interpretations align with those identified in Equation 1.

Moreover, to assess the moderation impact of GTI with GF and GOV on GTFP, Equation 1 is expanded by incorporating the interaction of $(GF \times GTI)$ and $(GOV \times GTI)$ in Equations 4, 5.

$$\begin{aligned}\operatorname{Ln} GTFP_{it} &= \varrho + \varphi_1 \ln REN_{it} + \varphi_2 \ln GF_{it} + \varphi_3 (GF \times GTI) \\ &+ \varphi_4 \ln GTI_{it} + \varphi_5 \ln GOV_{it} + \varphi_6 Z_{it} + \mu_{it}\end{aligned} \tag{4}$$

$$\begin{aligned}\operatorname{Ln} GTFP_{it} &= \rho + \phi_1 \ln REN_{it} + \phi_2 \ln GF_{it} + \phi_3 \ln GTI_{it} \\ &+ \phi_4 \ln GOV_{it} + \phi_5 (GOV \times GTI) + \phi_6 Z_{it} + \mu_{it}\end{aligned} \tag{5}$$

Where $GF \times GTI$ denotes the interaction term between green finance and green technology innovation in Equation 4, $GOV \times GTI$ refers to the relationship between green finance and green technological innovation in Equation 5. All other variables are defined as in Equation 1.

4.2 The data

China, the economy that is the second largest in the world, has long had serious issues with environmental pollution. To achieve sustainable economic development, the country actively promotes the establishment of an ecological civilization and participates in global sustainable development governance initiatives. In 2015, the country proposed the goal of "green development" and subsequently formulated and implemented a series of related economic policies around it. Against this backdrop, this study constructed a balanced panel dataset covering 30 provinces in China (Tibet was excluded due to severe data gaps) based on data reliability and availability. The dataset comprises 390 observations, covering the period from 2010 to 2022. This study seeks to examine the major determinants of economic sustainability, employing GTFP as a key metric.

Following Tone and Sahoo (2003) and Park et al. (2024), GTFP is assessed utilizing the Global Malmquist-Luenberger (GML) index, which is obtained through a non-radial, non-oriented super-efficiency SBM method. The GML indices for the 30 provinces were calculated using Max-DEA Ultra software, incorporating non-desired outputs. Input indicators include labor, capital, and energy: The employee number serves as a proxy for labor; the perpetual inventory approach is used to construct capital stock, which serves as a proxy, with real gross fixed capital formation as investment input and a constant depreciation rate of 9.6%, and energy is represented by the total energy consumption. Output indicators are divided into desirable and undesirable outcomes. The desired output is real GDP (base year 2006), adjusted for pricing considerations to reflect the level of economic development. Undesired outputs include emissions of industrial wastewater, sulfur dioxide, smoke, dust, and carbon dioxide, which represent environmental pollution levels. Table 1 displays the definitions for each variable.

Furthermore, REN, GTI, GOV, and GF are included as the explanatory variables. A majority of studies use the ratio of electricity generation from renewable sources to total electricity generation to evaluate the development of renewable energy (Song et al., 2022; Zhu et al., 2022). Drawing on Yu et al. (2021), the ratio of green patents to total patents is used to calculate GTI, according to the National Intellectual Property Administration of China. GOV is measured by fiscal expenditure as a percentage of regional GDP (Lee et al., 2024). Following the study of Liu et al. (2019), this study measures green finance across four dimensions: green credit, investment, securities, and insurance. To refine the indicator system, this study proposes adding an additional dimension that incorporates environmental protection support, considering fiscal policy (see Table 2). Furthermore, following Lee and Lee, 2022, this study calculates a comprehensive index using the entropy method for objective weighting.

Control variables include transportation infrastructure (TI), openness (OP), and industrial structure upgrading (IS), which is in line with previous research on green productivity and sustainable development (Hosan et al., 2022; Liu et al., 2024). Enhancements to road infrastructure can mitigate traffic congestion, thus reducing energy consumption and pollution emissions, which benefits GTFP (Zhao et al., 2022). To quantify infrastructure, this study uses the logarithm of highway mileage in each province. OP has an impact on a country's GTFP by optimizing its industrial structure and influencing technological spillovers (Zhang, 2021), it is measured by the share of goods and services traded in GDP. Following Zhao et al. (2024), IS is the value addition ratio between the secondary and tertiary sectors. To reduce data variability and ensure consistency, all variables are transformed into their logarithmic forms. Minor missing values are handled using interpolation techniques. Table 3 provides descriptions of the variables and the data sources.

TABLE 1 Constructing the green total factor productivity indicator system.

Category	Specific indicators	Indicator measurement	Sources
Inputs	Labor	Number of employed people	PSY
	Capital	Capital stock estimated using the perpetual inventory method	PSY
	Energy	Total electricity consumption	CEPY
Desired outputs	Regional GDP	Real GDP of each province	PSY
Undesired output	Pollutant emissions	Industrial wastewater emissions	CESY
		Industrial SO_2 emissions	CESY
		Industrial dust emissions CO_2 emissions	CESY

PSY, Provincial Statistical Yearbooks (https://data.stats.gov.cn/english/easyquery.htm?cn=E0103); CEPY, China Electric Power Yearbook (https://cnki.nbsti.net/CSYDMirror/trade/Yearbook/Single/N2021050269?z=Z025); CESY, China Environmental Statistical Yearbook (https://www.shujuku.org/china-environment-statistical-yearbook.html).

TABLE 2 A comprehensive assessment system for green finance.

Overall indicator	Sub-indicator	Indicators measurement	Sources
Green finance development index	Green credit	The ratio of interest expenditure within the total industry for six high energy-consuming sectors	PSY, CFY
	Green securities	The ratio of the market value of the six energy-intensive industries to the overall market value of A-shares	CSMAR
	Green insurance	The ratio of agricultural insurance income to the gross agricultural output value	CIY, CASY
	Green investment	The investment-to-gross domestic product (GDP) ratio for environmental pollution prevention	CESY
	Environmental support	The ratio of government spending on environmental protection to total government spending	CFY

PSY, Provincial Statistical Yearbooks (https://data.stats.gov.cn/english/easyquery.htm?cn=E0103); CFY, China Fiscal Yearbook (https://www.shujuku.org/china-finance-yearbook-2024.html); CSMAR, China Stock Market and Accounting Research (CSMAR) database; CIY, China Insurance Yearbook (https://www.shujuku.org/china-insurance-yearbook.html); CASY, China Agricultural Statistical Yearbook (https://cnki.nbsti.net/CSYDMirror/trade/Yearbook/Single/N2023030189?z=Z009); CESY, China Environmental Statistical Yearbook (https://www.shujuku.org/china-environment-statistical-yearbook.html).

TABLE 3 Variable description and data sources.

Variables	Symbol	Measurement	Sources
Green total factor productivity	GTFP	As calculated in the previous section	CSY, PSY, CESY
Renewable energy	REN	Ratio of renewable energy electricity generation to total electricity generation	CNIPA
Green technology innovation	GTI	Number of green patents divided by the total number of patents	CEPY
Green finance	GF	Comprehensive index of green finance	CISY, CESY, PSY, CIY, CASY, CFSY
Government intervention	GOV	Ratio of fiscal expenditure to regional GDP	PSY
Transportation infrastructure	TI	The logarithm of highway mileage	PSY
Openness	OP	Share of goods and services trade in GDP	PSY
Industrial structure upgrading	IS	Proportion of secondary sector added value to tertiary sector added value	CSY

CSY, China Statistical Yearbook (https://data.stats.gov.cn/english/); PSY, Provincial Statistical Yearbooks (https://data.stats.gov.cn/english/easyquery.htm?cn=E0103); CESY, China Environmental Statistical Yearbook (https://www.shujuku.org/china-environment-statistical-yearbook.html); CNIPA, China National Intellectual Property Administration (https://english.cnipa.gov.cn/col/col2942/index.html); CEPY, China Electric Power Yearbook (https://cnki.nbsti.net/CSYDMirror/trade/Yearbook/Single/N2021050269?z=Z025); CISY, China Industrial Statistics Yearbook (https://cnki.nbsti.net/CSYDMirror/trade/Yearbook/Single/N2014020031?z=Z012); CIY, China Insurance Yearbook(https://www.shujuku.org/china-insurance-yearbook.html); CFSY, China Financial Statistical Yearbook (https://pbocri.org.cn/jrnj.html); CASY, China Agricultural Statistical Yearbook (https://cnki.nbsti.net/CSYDMirror/trade/Yearbook/Single/N2023030189?z=Z009).

4.3 Estimation strategy

To ensure the reliability of the panel estimations, several standard diagnostic tests were conducted prior to model estimation. Specifically, cross-sectional dependence was assessed employing the CSD test as developed by Friedman (1937) and Pesaran (2004); heteroskedasticity was evaluated using the Breusch–Pagan test (Breusch and Pagan, 1979); serial correlation was examined using (Wooldridge, 2010); the Fisher-ADF and IPS panel unit root tests were used to check for stationarity;

TABLE 4 Summary statistics and correlation analysis.

Variables	GTFP	REN	GF	GTI	GOV	TI	OP	IS
Mean	0.695	5.584	0.320	9.553	0.245	11.689	0.260	1.125
Std. Dev	0.358	1.495	0.123	1.432	0.102	0.854	0.295	0.647
Min	0.089	0	0.083	5.625	0.106	9.390	0.000	0.494
Max	2.102	8.339	0.632	12.398	0.643	12.913	1.548	5.297
Observation	390	390	390	390	390	390	390	390
GTFP	1							
REN	0.199***	1						
GF	0.438***	0.542***	1					
GTI	0.439***	0.193***	0.502***					
GOV	−0.263***	0.0380	−0.635***	0.072	1			
TI	0.041	0.343***	0.579***	0.126**	−0.657***	1		
OP	0.246***	−0.298***	0.382***	−0.168***	−0.370***	−0.024	1	
IS	−0.216***	0.029	−0.073	−0.011	0.191***	−0.067	−0.010	1

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. GTFP, denotes Green Total Factor Productivity; REN, represents renewable energy consumption; GF, is green finance; GTI, refers to green technological innovation; GOV, is government intervention; TI, indicates transportation infrastructure; OP, denotes openness; and IS, represents industrial structures.

cointegration long-run relationships were examined through cointegration tests proposed by Kao (1999) and Westerlund (2005); and multicollinearity was diagnosed using variance inflation factors (VIF). Moreover, the appropriate specification between fixed-effects and random-effects models was determined using the Hausman test (Hausman, 1978).

Based on the diagnosis results, this study uses the Generalized Least Squares (GLS) method as the main estimation approach. Further, serial correlation and cross-sectional dependence in the error terms are also addressed using Driscoll-Kraay (D-K) standard errors with a fixed-effects model. This study employs the two-step System GMM method established by Blundell and Bond (1998) to enhance the robustness of the results and reduce potential endogeneity in a dynamic panel scenario. Using the System GMM method, the lagged dependent variable and the main explanatory variables (REN, GTI, GF, and GOV) are set as endogenous, and the other control variables are set as exogenous. The instruments are built from lagged values starting from period t-2, and the instrument set is collapsed to limit the number of instruments. Windmeijer-corrected standard errors are used for the two-step estimates.

5 Empirical results and discussion

5.1 Descriptive statistics and preliminary tests

This study conducts empirical analysis with STATA 18. As a first step, Table 4 displays the descriptive statistics and correlation matrix. The mean value of GTFP is 0.695, and its standard deviation is 0.358. The average value of REN is 5.584, and the mean value of GTI is 9.553. Among all variables, GTI and REN have the largest standard deviations, which shows that these variables vary greatly across provinces. On the other hand, the standard deviations of GF and GOV are 0.123 and 0.102, respectively, while their mean values are 0.320 and 0.245. Furthermore, the correlation results indicate generally positive relationships between GTFP and the explanatory variables, except for GOV, IT, and IS.

To assess multicollinearity, a variance inflation factor test was performed (see Table 5). There is no evident multicollinearity among the variables, as shown by the average VIF value of 2.84, which is below the normal standard of 5. Following this, the IPS and ADF tests were used to check whether the variables were stationary.

The outcomes of unit root tests in Table 6 indicate that all the variables except for GTI, TI, and IS are stationary at “first difference, stationary [I (0)]”. Following this, this study assesses the existence of long-run relationships using the Westerlund cointegration, Pedroni, and Kao tests In Table 7. The significant p-values from the Westerlund panel cointegration test indicate a long-term link among the variables. Additionally, a series of diagnostic tests are conducted, as presented in Table 8. These comprise the Hausman test, the Wooldridge autocorrelation test, and the Breusch-Pagan heteroskedasticity test.

The Hausman test rejects the null hypothesis at the 5% significance level, thus the fixed effects model is used in Table 8. Furthermore, the Wooldridge test for autocorrelation and the Breusch-Pagan test for heteroskedasticity are both statistically significant, suggesting autocorrelation and heteroskedasticity in the model, respectively.

Additionally, Table 9 shows the results of the Friedman (1937) and Pesaran (2004) cross-sectional dependence tests, indicating that cross-sectional dependence exists in the dataset. To identify these

TABLE 5 Variance inflation factor (VIF) test for multicollinearity.

Variables	VIF	1/VIF
REN	1.90	0.942
GTI	5.20	0.192
GF	3.44	0.290
GOV	3.22	0.310
TI	3.09	0.323
OP	1.98	0.505
IS	1.06	0.942
Mean VIF	2.84	

REN, represents renewable energy consumption; GF, is green finance; GTI, refers to green technological innovation; GOV, is government intervention; TI, indicates transportation infrastructure; OP, denotes openness; and IS, represents industrial structures. A VIF, value under 10 and a 1/VIF, value exceeding 0.1 suggest no evidence of significant multicollinearity. The findings indicate that multicollinearity is not an issue in this model.

TABLE 6 Panel unit root tests.

Variable	IPS test		ADF		Outcome
	I (0)	I (1)	I (0)	I (1)	
GTFP	−3.640***	−7.891***	−3.640***	6.723***	I (0)
REN	−3.000***		−2.300***		I (0)
GTI	−1.200		−1.031		I (1)
GF	−3.911***		−3.334***		I (0)
GOV	−4.823***	−7.600***	−4.823***	10.549***	I (0)
TI	−1.542		0.624		I (1)
OP	−4.113***		0.248***	12.198***	I (0)
IS	−2.430***		0.407		I (1)

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. IPS, refers to the Im-Pesaran-Shin panel unit root test, while ADF, represents the Augmented Dickey-Fuller panel unit root test. I (0) and I (1) indicate stationarity at levels and first differences, respectively. GTFP, denotes Green Total Factor Productivity; REN, represents renewable energy consumption; GF, is green finance; GTI, refers to green technological innovation; GOV, is government intervention; TI, indicates transportation infrastructure; OP, denotes openness; and IS, represents industrial structures.

TABLE 7 Co-integration test results.

Method	Test statistics	Statistic	p-value
Westerlund test	Variance ratio	11.287***	0.000
Kao test	Modified Dickey-Fuller t	−2.523***	0.006
	Dickey-fuller t	−4.304***	0.000
	Augmented Dickey-Fuller t	−5.787***	0.000
	Unadjusted modified Dickey-Fuller t	−3.044***	0.001
	Unadjusted Dickey-Fuller t	−4.545***	0.000

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

issues, this study estimates Equations 1–5 (illustrated with Models I to V) using the GLS and Driscoll–Kraay (D-K) estimators, with the results reported in Tables 10, 11.

TABLE 8 Diagnostic tests.

Test statistics	Value
Hausman test	46.49*** (0.000)
Breusch pagan (B-P) heteroskedasticity test	12.02*** (0.000)
Wooldridge autocorrelation test	922.32*** (0.000)

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

TABLE 9 Cross sectional dependence test.

Test statistics	Value
Pesaran test	56.016* (0.000)
Friedman test	255.288*(0.000)

* denotes significance at the 1% level ($p < 0.01$).

TABLE 10 Baseline and extended models estimated with generalized least squares.

Variables	GTFP	GTFP	GTFP	GTFP	GTFP
	Model-I	Model-II	Model-III	Model-IV	Model-V
REN	0.054***	0.009	0.061***	0.012***	0.079***
	(0.019)	(0.033)	(0.019)	(0.005)	(0.020)
GF	2.153***	2.066***	2.194***	0.092	2.441***
	(0.342)	(0.342)	(0.337)	(0.089)	(0.366)
GTI	0.091***	0.076***	0.106***	0.045***	0.088***
	(0.017)	(0.018)	(0.017)	(0.012)	(0.019)
GOV	−1.227***	−1.222***	−2.912***	−0.526***	−1.556***
	(0.216)	(0.215)	(0.533)	(0.130)	(0.242)
REN^2		0.008**			
		(0.004)			
GOV^2			2.489***		
			(0.722)		
GF × GTI				0.089*	
				(0.053)	
GOV × GTI					0.046**
					(0.023)
TI	−0.160***	−0.172***	−0.164***	−0.073***	−0.219***
	(0.047)	(0.047)	(0.046)	(0.018)	(0.048)
OP	0.002	−0.041	0.002	−0.009	0.024
	(0.064)	(0.067)	(0.063)	(0.005)	(0.064)
IS	−0.029**	−0.029**	−0.031**	0.124***	−0.029**
	(0.015)	(0.014)	(0.015)	(0.039)	(0.015)
Constant	1.225**	1.568***	1.483***	1.103***	1.747***
	(0.500)	(0.517)	(0.498)	(0.217)	(0.505)
Observations	390	390	390	390	390
Provinces	30	30	30	30	30

Green total factor productivity (GTFP) is the dependent variable. REN, represents renewable energy consumption; GF, is green finance; GTI, refers to green technological innovation; GOV, is government intervention; TI, indicates transportation infrastructure; OP, denotes openness; and IS, represents industrial structures. Standard errors in parentheses, ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

5.2 Results and discussion

5.2.1 Impacts of renewable energy, green finance, green technology innovation, and government intervention on green total factor productivity (RQ1)

Table 10, Model I, reports the baseline estimates of the impact of key explanatory variables on GTFP. The results indicate that REN has a positive influence on GTFP, with an estimated coefficient of 0.054, which is statistically significant at the 1% level. Suggesting that higher use of renewable energy contributes to green productivity performance, verifying hypotheses 1. This is consistent with the findings of Li M. et al. (2024) and Xie et al. (2021), who argue that REN can not only improve energy efficiency but also promote technological innovation, thereby promoting the growth of GTFP. However, this conclusion is contrary to the research of Murshed et al. (2022), who argue that the renewable energy use might impede the green transition and damage the environment. The construction of renewable energy facilities typically requires substantial capital investment and advanced technological support, resulting in high initial operating expenses. This leads to continued reliance on traditional energy sources in the early stages of development, exacerbating environmental pressures and increasing carbon dioxide emissions (Behera B. et al., 2024).

GF significantly increases GTFP, with a coefficient of 2.153 and a significance level of 1%. Showing that GF can promote GTFP by

TABLE 11 Baseline and extended models estimated with driscoll–kraay.

Variables	GTFP	GTFP	GTFP	GTFP	GTFP
	Model-I	Model-II	Model-III	Model-IV	Model-V
REN	0.060**	0.019	0.066**	0.059**	0.066**
	(0.026)	(0.029)	(0.025)	(0.025)	(0.024)
GF	0.740***	0.695***	0.805***	0.663***	0.765***
	(0.175)	(0.166)	(0.161)	(0.183)	(0.149)
GTI	0.077***	0.069***	0.077***	0.089***	0.088***
	(0.018)	(0.022)	(0.017)	(0.021)	(0.018)
GOV	−1.235**	−1.221**	−3.797***	−1.223**	−1.265**
	(0.545)	(0.535)	(0.651)	(0.548)	(0.538)
REN^2		0.006			
		(0.005)			
GOV^2			4.334***		
			(0.469)		
GF × GTI				0.019*	
				(0.011)	
GOV × GTI					0.085*
					(0.047)
TI	−0.157**	−0.164**	−0.220***	−0.145**	−0.170*
	(0.067)	(0.069)	(0.065)	(0.065)	(0.081)
OP	−0.048	−0.077	−0.030	−0.025	0.010
	(0.068)	(0.070)	(0.058)	(0.076)	(0.077)
IS	−0.035***	−0.035***	−0.039***	−0.032***	−0.028***
	(0.008)	(0.009)	(0.007)	(0.007)	(0.007)
Constant	2.898***	3.015***	3.997***	2.542**	1.344
	(0.881)	(0.935)	(0.883)	(0.864)	(1.153)
Observations	390	390	390	390	390
Number of groups	30	30	30	30	30

Green total factor productivity (GTFP) is the dependent variable. REN, represents renewable energy consumption; GF, is green finance; GTI, refers to green technological innovation; GOV, is government intervention; TI, indicates transportation infrastructure; OP, denotes openness; and IS, represents industrial structures. Standard errors in parentheses, ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

directing funds to the environmental protection industry. Hypotheses 2 is verified. This result is consistent with GF's core position, which serves as a financial instrument combining economic performance with environmental goals (Hussain et al., 2024). GF introduces capital and technology into the clean field, which can not only reduce the environmental but also expand the green industry, which significantly promotes the improvement of GTFP (Odugbesan et al., 2021). Similar evidence is also reported by Nosheen et al. (2021), Suki et al. (2022), and Liu and Dong (2021).

Similarly, GTI exerts a positive influence on GTFP, with a significant level of 1% and a coefficient of 0.091. This shows that GTI is the key to improving productivity, and the essential way is to promote industrial structure upgrading and improve energy efficiency (Cheng et al., 2024; Jiang et al., 2024). For example, GTI will support low-carbon knowledge-based enterprises and optimize the resource utilization rate of traditional industries, thus directly boosting GTFP and promoting the economy's transition to a green, low-carbon economy. This is in line with the conclusion of Jiakui et al. (2023). Confirming hypothesis 3.

In contrast, GOV exhibits a negative association with GTFP, suggesting that policies aimed at promoting green growth may inadvertently cause inefficiencies and resource misallocation. This is consistent with o Liu et al. (2023). In conclusion, REN, GF, and GTI are key drivers of green productivity gains, whereas inappropriate government intervention appears to undermine production efficiency. Additionally, the baseline models are

TABLE 12 Regional heterogeneity analysis of green total factor productivity.

Variables	GTFP	GTFP	GTFP
	East region	Center region	West region
GF	0.646***	1.258***	0.522***
	(0.072)	(0.160)	(0.093)
REN	−0.005	0.093***	0.017***
	(0.006)	(0.010)	(0.006)
GTI	0.120***	−0.152***	−0.005
	(0.006)	(0.014)	(0.009)
GOV	−0.361***	0.787***	−0.387***
	(0.106)	(0.218)	(0.120)
IT	−0.144***	0.218***	0.076***
	(0.014)	(0.029)	(0.014)
OP	−0.109***	−0.470***	−0.475***
	(0.025)	(0.170)	(0.110)
IS	0.001	−0.010	−0.026***
	(0.006)	(0.015)	(0.005)
Constant	0.901***	−2.015***	−0.623***
	(0.170)	(0.406)	(0.158)
Observations	143	130	117
Provinces	11	10	9

Green total factor productivity (GTFP) is the dependent variable. REN, represents renewable energy consumption; GF, is green finance; GTI, refers to green technology innovation; GOV, is government intervention; TI, indicates transportation infrastructure; OP, denotes openness; and IS, represents industrial structures. Standard errors in parentheses, ***p < 0.01, **p < 0.05, *p < 0.1.

re-estimated employing fixed-effects estimation with Driscoll-Kraay standard errors to address cross-sectional dependence (see Table 11). The estimates remain the same as the GLS results, which indicate that the major conclusions are still reliable.

5.2.2 Nonlinear effects of renewable energy and government intervention on green total factor productivity (RQ2)

Model II and Model III in Table 10 include the squared terms of REN^2 and GOV^2 to test nonlinear effects on GTFP. In Model II, REN's linear term is not statistically significant. However, at the 5% level, the squared term is significant and positive. These results indicate that REN in China boosts GTFP through increasing marginal gains as the sector grows larger. This result agrees with Dong et al. (2022), who suggest that GTFP benefits from the "learning-by-doing" mechanism as renewable energy is scaled up. But this finding differs from of Li M. et al. (2024), who report that the marginal effect of REN on GTFP is positive but decreases as renewable energy use rises.

Furthermore, in Model III of Table 10, GOV has a significantly negative linear effect on GTFP. Indicating that mismatches in resource allocation or policy implementation may constrain improvements in green productivity when government engagement is limited. At the 1% level, the GOV quadratic term is positive and significant. This illustrates the U-shaped relationship between GTFP and GOV. The U-shaped curve has an inflection point of 0.585, which falls within the GOV observation range of 0.106–0.643. In other words, GOV will have a positive effect on GTFP only if the intervention intensity crosses this turning point, which supports hypothesis 4. This is consistent with Liao and Zhang (2023), they believe the initial GOV will likely result in an inefficient use of resources, and that intervention can increase the system's efficiency once the institutional system and policy tools are enhanced. Therefore, to effectively foster sustainable transformation, GOV should be kept above a reasonable threshold while optimizing the governance structure.

5.2.3 Moderating effects of green finance and government intervention on the relationship between green technology innovation and green total factor productivity (RQ3)

Models IV and V in Table 10 examine the moderating effects of GF and GOV on the link between GTI and GTFP. In Model IV, at the 10% level, the estimated interaction impact between GF and GTI is positive and significant. This result suggests that GF can strengthen the positive effect of GTI on productivity, which validates hypothesis 5. Further, Figure 3 shows the marginal effects of GTI on GTFP at different levels of green finance,

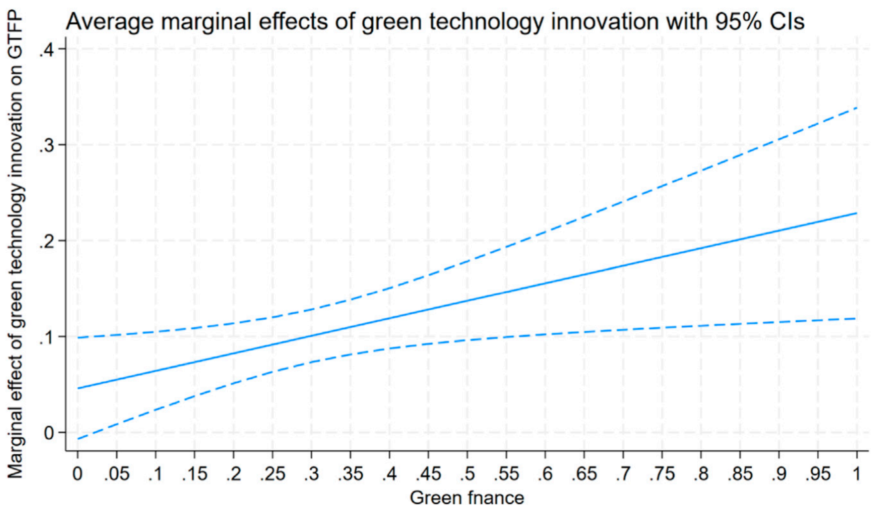

FIGURE 3
Marginal effect of green technology innovation on green total factor productivity conditional on green finance. Note: The solid line depicts the average marginal effect, while the dotted lines indicate 95% confidence intervals. Source: Authors' own work.

together with the 95% confidence intervals. When the level of GF is low, the impact of GTI on productivity is not statistically significant. As GF increases, this effect becomes positive and significant. A possible reason is that when GF is underdeveloped, GTI faces severe financing constraints and does not contribute to productivity improvement. However, as the green finance system gradually improves and appropriate financial instruments are matched, the financial pressure on innovation activities can be alleviated, innovation risks can be diversified, and resources can be guided to the green technology field, thereby improving productivity. This aligns with the findings of Zhou K. et al. (2023), which indicate that by mobilizing social capital and enhancing long-term financial support, financing constraints and market uncertainty can be alleviated, and investment in green and innovative technologies can be promoted, thereby improving productivity. Further, green finance's incentives for groundbreaking innovation require more suitable financial instruments that can bear higher risks (Raman et al., 2025). Furthermore, Kwilinski et al. (2025) pointed out that the availability of venture capital and the maturity of the financial system often influence the function of GF in fostering innovation.

Similarly, Model V in Table 10 illustrates the moderating role of GOV on the impact of GTI on GTFP. The coefficient of the GOV × GTI interaction term is statistically significant and positive. This shows that GOV can strengthen the positive role of GTI in GTFP, which also verifies Hypothesis 6. This conclusion is in line with China's long-term innovation strategy. The initial obstacles to adopting green technologies can gradually be eliminated by the ongoing policies that support the "dual carbon" goals (Xu et al., 2024). As Liang and Li (2023) also confirmed that continuous government support will strengthen the innovation system and help the technological potential turn into real productivity growth. These findings also suggest that policymakers should address short-term infrastructure investment and long-term innovation support separately. Furthermore, government intervention must also address the differentiated needs of various industries and implement dynamic adjustments.

5.2.4 Regional heterogeneity analysis of green total factor productivity

There are differences in resource endowments and financial development levels in different regions. This study conducts sub-sample regressions for the eastern, central, and western areas to examine the regional heterogeneity in the impact of GF on GTFP The results are reported in Table 12. GF exerts a positive and statistically significant influence on GTFP across three regions. This finding is consistent with Zhang M. et al. (2024), who show that green finance generally supports green innovation and improves resource allocation at the national level.

The findings show that GF has the greatest effect on GTFP in the central region, with a coefficient of 1.258 ($p < 0.01$). This finding differs from Li et al. (2023), who report larger effects in the eastern region. One likely explanation is that the central region has long faced stiffer restrictions on GF, thus, the expansion of GF releases unmet demand for green investment and leads to larger marginal productivity gains, which creates a clear catch-up effect.

GF has a smaller but still significant impact on GTFP in the eastern region (coefficient = 0.646, $p < 0.01$). The reason may be that the foundation of environmental governance in the eastern region is already strong, and the marginal income of new green financial investment is declining. This aligns with the conclusions of (Tan and Zhou, 2025).

GF has the weakest impact on GTFP in the western region (coefficient = 0.522, $p < 0.01$). This may be due to factors such as a uniform economic structure, underdeveloped markets, and stricter institutional constraints, which limit GF's effectiveness in boosting GTFP. Lv et al. (2021) also pointed out that there are significant differences in financial absorptive capacity among regions in China.

Similarly, there are regional differences in the effect of GTI on GTFP; it is positive in the east, negative in the center, and not statistically significant in the west of China. In eastern China, GTI has a positive relationship with GTFP, reflecting the region's relatively strong absorptive capacity and well-developed green technology market (Ding and Hu, 2025), which can effectively

TABLE 13 Robustness test utilizing the two-step system generalized method of moments.

Variables	GTFP	GTFP	GTFP	GTFP	GTFP
	Model-I	Model-II	Model-III	Model-IV	Model-V
L.GTFP	1.177***	0.999***	1.036***	1.180***	1.057***
	(0.111)	(0.101)	(0.180)	(0.107)	(0.036)
REN	0.142**	0.696*	0.315*	−0.135**	0.001
	(0.064)	(0.345)	(0.190)	(0.062)	(0.009)
GF	0.065	0.457	−0.441	0.009	−0.008
	(0.387)	(0.430)	(0.553)	(0.368)	(0.104)
GTI	0.084**	0.021	0.181**	0.084**	0.055***
	(0.040)	(0.033)	(0.082)	(0.040)	(0.018)
GOV	−1.823**	1.006	−0.112*	1.785**	0.677***
	(0.908)	(0.746)	(0.065)	(0.867)	(0.182)
REN^2		0.063*			
		(0.033)			
GOV^2			0.144**		
			(0.062)		
GF × GTI				0.058	
				(0.122)	
GOV × GTI					0.108**
					(0.045)
TI	0.148	0.095	0.293	0.138	−0.018
	(0.142)	(0.099)	(0.227)	(0.138)	(0.027)
OP	−0.426***	−0.416***	−0.590**	−0.421***	−0.087**
	(0.124)	(0.118)	(0.300)	(0.123)	(0.042)
IS	−0.014	−0.012	−0.060	−0.014	−0.008
	(0.019)	(0.016)	(0.053)	(0.017)	(0.008)
Constant	−2.156	0.224	−4.461*	−2.052	−0.434
	(1.522)	(1.112)	(2.452)	(1.488)	(0.287)
AR1/AR2	0.003/0.101	0.047/0.755	0.050/0.374	0.002/0.084	0.000/1.00
Hansen test	0.306	0.429	0.957	0.410	0.640
Observations	360	360	360	360	360
Provinces	30	30	30	30	30

Green total factor productivity (GTFP) is the dependent variable. REN, represents renewable energy consumption; GF, is green finance; GTI, refers to green technological innovation; GOV, is government intervention; TI, indicates transportation infrastructure; OP, denotes openness; and IS, represents industrial structures. The lagged dependent variable and key explanatory variables (REN, GF, GTI, and GOV) are treated as endogenous, while the control variables are assumed to be exogenous. Endogenous variables are instrumented using their own lagged values starting from t−2. The instrument matrix collapses to mitigate instrument proliferation. Windmeijer-corrected standard errors are reported. AR (1), AR (2), and Hansen test statistics are provided to assess model validity. Standard errors in parentheses, ***p < 0.01, **p < 0.05, *p < 0.1.

transform innovation investment into green productivity growth. However, GTI exhibits a significant adverse effect on GTFP in the central region. Which may be because the local technological innovation has not really been transformed into a substantial green transformation. During the process of industrial relocation, innovation efforts may be concentrated on sustaining or expanding energy-intensive production, resulting in a form of green technology misallocation that temporarily suppresses GTFP (Tian et al., 2025). However, in the west, there is no statistically significant impact of GTI on GTFP. The translation of invention into green productivity outcomes is impeded by weak technological diffusion and institutional limitations (Liu et al., 2025).

TABLE 14 Dumitrescu–hurlin panel granger causality test (first differences).

Variables	GTFP	REN	GF	GTI	GOV	TI	OP	IS
GTFP		5.215	5.179	4.262	2.688	3.015	3.523	2.673
		{16.325***}	{16.187***}	{12.635***}	{6.538***}	{7.805***}	{9.773***}	{6.481***}
		[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
REN	1.705		5.757	4.225	4.447	3.688	3.232	2.700
	{2.732***}		{10.290***}	{6.094***}	{6.701***}	{4.620***}	{8.647***}	{6.583***}
	[0.005]		[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
GF	1.210	3.501		6.131	0.844	1.250	1.107	1.094
	{0.814}	{4.110***}		{11.314***}	{-0.603}	{0.969}	{0.413}	{0.364}
	[0.416]	[0.000]		[0.000]	[0.547]	[0.332]	[0.679]	[0.716]
GTI	0.353	2.432	3.939		1.875	0.685	1.104	1.037
	{-2.505**}	{1.185}	{5.312***}		{3.887***}	{-1.218}	{0.403}	{0.143}
	[0.012]	[0.236]	[0.000]		[0.000]	[0.223]	[0.687]	[0.886]
GOV	5.012	2.973	3.454	3.648		1.516	1.592	2.107
	{15.537***}	{7.640***}	{9.505***}	{10.257***}		{1.997**}	{2.292**}	{4.289***}
	[0.000]	[0.000]	[0.000]	[0.000]		[0.046]	[0.023]	[0.000]
TI	2.548	2.181	2.908	2.301	1.334		0.900	1.351
	{5.997***}	{4.573***}	{7.389***}	{5.037***}	{1.293}		{-0.387}	{1.358}
	[0.000]	[0.000]	[0.000]	[0.000]	[0.196]		[0.698]	[0.174]
OP	2.107	2.393	4.468	5.212	3.249	3.105		2.127
	{4.289***}	{5.395***}	{13.432***}	{16.314***}	{8.712***}	{8.154***}		{4.366***}
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]		[0.000]
IS	3.087	2.442	2.279	2.256	4.294	1.716	2.412	
	{8.081***}	{4.818***}	{4.956***}	{4.867***}	{12.756***}	{2.771***}	{5.470***}	
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.005]	[0.000]	

GTFP, denotes Green Total Factor Productivity; REN, represents renewable energy consumption; GF, is green finance; GTI, refers to green technology innovation; GOV, is government intervention; TI, indicates transportation infrastructure; OP, denotes openness; and IS, represents industrial structures. The Dumitrescu–Hurlin panel causality test is conducted using first-differenced variables. Lag length is selected based on standard information criteria. The results indicate that the detected Granger-type relationships are primarily evident at one-period lags, while they weaken under longer lag structures. *, **, and *** denote 10%, 5%, and 1% significance levels. (.), {.} and [.] indicate W-bar, Z-bar, and P-values, respectively.

Further diagnostic tests show that the variance inflation factor (VIF) values for the estimated models are low in all regions. The VIF values are 2.77 for eastern China, 1.81 for central China, and 2.86 for western China. Multicollinearity is not an important problem in regional estimation, as all these values are far below the threshold of 10. Therefore, reflect real differences in the efficiency of green technology conversion, the alignment of industrial structures, and the conditions that support innovation.

5.3 Robustness tests

This study re-estimates the baseline models using the two-step System GMM method to address potential endogeneity and verify the robustness of the results. Table 13 presents the outcomes.

Model-I in Table 13, both REN and GTI have positive effects on GTFP. GTFP improves by 0.142% and 0.084% per unit increase in REN and GTI, respectively. GF also has a positive but statistically insignificant influence on GTFP. An explanation might exist in institutional and policy frictions, including weak policy coordination, a regulatory preference for low-risk projects, and a green credit orientation that emphasizes scale over efficiency, all of which might hinder the crucial role of green finance in promoting productivity-driven green innovation (Zhang and Vigne, 2021). However, the results show that GOV reduces GTFP in China, with an estimated effect of −1.823%.

In Model II, the quadratic term of renewable energy exhibits a significant positive influence on GTFP (coefficient = 0.063, $p < 0.05$). Model III shows a U-shaped relationship between GOV and GTFP, with a nonlinear term coefficient of 0.144 and an inflection point of 0.39. This shows that when the level of intervention is low, its impact is significantly negative; only when the intervention intensity exceeds a certain level can it have a beneficial effect. In Model IV, while both GF and GTI boost GTFP, the coefficient of their

FIGURE 4
Summary of the main findings. Note: GTFP denotes Green Total Factor Productivity; REN represents renewable energy consumption; GF is green finance; GTI refers to green technological innovation; GOV is government intervention; TI indicates transportation infrastructure; OP denotes openness; and IS represents industrial structures. "+" ("−") indicates a positive (negative) relationship between variables. Source: Authors' elaboration based on the study's empirical results.

interaction term is positive but not statistically significant. One possible explanation is that the institutional and structural constraints of China's green financial system have weakened its role in promoting green technological progress and productivity improvement. In Model V, both GOV and GTI show positive direct effects on GTFP. Furthermore, their interaction term is found to provide a significant boost to GTFP.

The model diagnostics confirm estimation reliability. The Arellano-Bond AR (1) test identifies significant first-order autocorrelation, whereas the AR (2) test fails to reject the null hypothesis of no second-order serial correlation, confirming proper model specification. The Hansen J-test shows that the overidentifying restrictions are valid, confirming instrument appropriateness.

Although the explanatory variables exhibit significant correlations with the dependent variable, correlation alone does not imply structural causality. Therefore, this study utilizes the Dumitrescu-Hurlin (D-H) panel causality test to investigate Granger causality among variables, specifically whether the lagged values of one variable can predict the current values of another. The D-H test allows cross-sectional dependence and is appropriate for heterogeneous panel data, and it is applicable when the variables are stationary in levels or first differences (Sethi et al., 2024). The lag length is selected based on standard information criteria, and alternative lag specifications are examined as robustness checks. The results indicate that the detected Granger-type relationships are primarily evident at one-period lags, while they weaken under longer lag structures.

The results reported in Table 14 provide evidence of short-run Granger-type predictability between REN, GOV, IS, and GTFP, suggesting mutually reinforcing temporal linkages. In addition, GOV is found to Granger-cause REN, GTI, OP, and IS, while exhibiting a unidirectional predictive relationship with GF and TI. The control variables TI, OP, and IS also display bidirectional Granger-causal links with GTFP.

Figure 4 shows a visual summary of the results, which are consistent across the different estimating methodologies employed.

6 Conclusion

The synergistic advancement of REN, GF, GTI, and GOV is a key path to improving GTFP and driving high-quality economic development. This study examines the impacts of RED, GF, GTI, and GOV on GTFP across 30 Chinese provinces over the period 2010–2022, using GLS, Driscoll–Kraay, and system GMM estimators. The following are the key findings: In response to RQ1, the findings indicate that REN, GTI, and GF significantly enhance GTFP in China, with coefficient estimates of 0.054, 0.091, and 2.153, respectively, all statistically significant at conventional levels ($p < 0.01$). Further research revealed that the effect of GF on GTFP is different across regions. The central part is the strongest (1.258, $p < 0.01$), followed by the eastern part (0.646, $p < 0.01$) and the western part is the weakest (0.522, $p < 0.01$). Regarding RQ2, the result shows a U-shaped relationship between GOV and GTFP. However, no significant nonlinear relationship is found between

REN and GTFP. In response to RQ3, the interaction analysis suggests that the GF and GOV significantly strengthen the positive impact of GTI on GTFP.

Based on the above research findings, several key policy implications can be derived: (1) The government should continue to increase the proportion of renewable energy in energy consumption, facilitating the energy structure transformation. Through continuously increasing investment in clean energy infrastructure like photovoltaic and wind power, and increasing investment in cleaning technology R&D. In light of this, the government should also keep enhancing the system of green finance instruments, alleviating corporate financing constraints, and effectively guiding social capital towards green industries. (2) Considering the non-linear relationship between government intervention and green total factor productivity. Policy design should be customized to the unique characteristics of each province, avoiding a "one-size-fits-all" approach. For provinces with lower levels of intervention such as Gansu, the emphasis should be on enhancing institutional rationality and allocating resources. By boosting infrastructure spending, raising subsidies for green technology R&D, strengthening the coordination between industrial and financial policies, and directing production factors towards intelligent and green fields. Like Jiangsu and Zhejiang provinces, which have higher intervention intensity, they should prioritize policies that enhance the quality of policy tools and the efficacy of governance. By reducing universal subsidies, strengthening the role of market mechanisms such as carbon trading and green credit, and using targeted subsidies and industry technical standards, enterprises can be encouraged to carry out substantive technological upgrades. (3) Furthermore, recognizing that both GF and GOV strengthen the positive effect of GTI on GTFP. Policy measures ought to emphasis more on enhancing the green finance system and encouraging private capital to invest in green technology. Meanwhile, the government needs to optimize the innovation environment, increase support for green technology research and development, and promote the deep integration of green finance and technological innovation. As a result, it effectively drives long-term productivity growth and lays a solid foundation for sustainable economic development.

Although this study provides valuable conclusions, it also has some limitations. First, due to data availability limitations, this study only covers the period up to 2022. Making it difficult to fully assess the long-term impact of recent major global public events and frequent extreme weather events on GTFP. Second, although the innovation indicators used in this study are relevant, they fail to fully reflect the quality differences in technological progress and the technology diffusion effect, especially failing to distinguish between substantive and strategic green innovation. Future research could address these limitations by extending the sample period, systematically assessing the long-term effects of global shocks and extreme weather on GTFP, and incorporating firm-level data to explore the micro-mechanism of green technology diffusion and innovation adoption.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

CL: Data curation, Formal Analysis, Funding acquisition, Methodology, Project administration, Software, Writing – original draft, Writing – review and editing. BP: Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Writing – original draft, Writing – review and editing. ZW: Conceptualization, Formal Analysis, Investigation, Software, Supervision, Visualization, Writing – review and editing.

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