

The Pathways of Green Technology Innovation to Economic Growth Quality: Evidence from China

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Abstract. In the context of global shift towards green and low-carbon development, the role and path of green technological innovation in improving the quality of economic growth remain to be fully elucidated. Using panel data from 30 Chinese provinces spanning 2011 to 2023, this study establishes a three-dimensional index framework including green total factor productivity, industrial structure upgrading index, and carbon intensity, and uses fixed effect and mediating effect models for empirical analysis. The empirical findings indicate that green technology innovation mainly drives the quality of economic growth through the synergy between industrial structure upgrading (29.8% of the mediating effect) and energy efficiency improvement (55.9% of the mediating effect), and the synergistic effect between green technology and digital infrastructure is significantly stronger in eastern China than that in the central and western regions (the central effect is not significant, and the western region is only marginally significant at the 10% level). The results of this study provide an empirical basis for solving the "last mile" problem of green technology transformation and formulating differentiated regional green innovation policies.

Keywords: green technology innovation, economic growth quality, digital infrastructure, mediating effect, regional heterogeneity

1. Introduction

Global warming and resource scarcity are intensifying, and green development and low-carbon transformation have become international consensus [1]. In this context, China has positioned green technology innovation as the cornerstone of its national strategy. This commitment is clearly reflected in its "dual carbon" goals and the "14th Five-Year Plan" green economic development plan, further highlighting the crucial importance of green technology.

However, the current role of green technological innovation in promoting the quality of economic growth has not been fully released, and it is facing systemic bottlenecks composed of external constraints, internal mechanisms and resource barriers. At the level of external constraints, China is facing a serious problem of "technology dependence". As US-led trade conflicts and technology blockades continue, the introduction of key green technologies and independent innovation are hindered, posing a major external challenge [2]. At the level of internal mechanisms, there is a problem of "failure of the transformation mechanism of scientific and technological achievements". The traditional transformation model has led to many problems such as the disconnection between the direction of technological innovation and market demand and the insufficient degree of technology

convertibility, which reflects the core contradiction between supply and demand within the innovation system [3]. At the level of resource barriers, "financing constraints" constitute a direct dilemma for micro entities. As the main body of innovation, technology-based enterprises have long faced the problem of insufficient R&D funds, and even if there are good technology and market opportunities, it is difficult to land due to lack of resources [4]. These three factors are intertwined and jointly restrict the effectiveness of green technological innovation.

Existing studies have reached a basic consensus on the association between green technology innovation and economic growth quality, confirming the moderating effects of variables such as environmental regulation and digital economy. However, there are still multidimensional theoretical gaps and methodological limitations. For example, Huang Shiqi focuses on the linear impact of GDP growth, and Zhang Xuechao introduces a coupling coordination degree model to reveal regional differences, but fails to construct a more comprehensive evaluation system to accurately capture the multidimensional impact of innovation [5,6]. At the level of mechanism research, although scholars have noted regional heterogeneity, there is a lack of systematic deconstruction of the deep drivers behind differences, such as institutional environment and barriers to technological transformation [7]. These drivers include the institutional environment, obstacles to technological transformation. In particular, the digital economy may lead to a widening of the digital divide, and its own high energy consumption will also offset these risks, which have not yet been fully integrated into the analytical perspective. Fan Dan et al. have difficulty reflecting the synergy of policy combinations in their isolated analysis of environmental regulation, while Bai et al.'s macro model is explanatory but lacks connection with micro firm behavior and fails to fully reveal the transmission mechanism [8,9].

Against this backdrop, this paper intends to systematically analyze the dual paths of green technology innovation that affect the quality of economic growth, namely industrial structure upgrading and energy efficiency improvement. In order to achieve this goal, this study establishes a three-dimensional evaluation system of "efficiency-structure-sustainability" based on panel data of 30 Chinese provinces from 2011 to 2023, which makes up for the lack of measurement of a single GDP dimension. This paper also constructs a moderating effect model by introducing interactive terms to conduct an empirical test. Compared with the existing literature, the marginal contribution of this study is mainly reflected in three aspects. The transmission mechanism of the dual intermediary path is systematically quantified, and the unexpected negative moderating effect of digital infrastructure is revealed, thus offering a robust empirical basis for the formulation of green innovation policies in differentiated regions.

2. Research methods

2.1. Theoretical model construction

This study establishes a three-dimensional analysis framework of "efficiency-structure-sustainability" to systematically assess the quality of economic growth. Among them, the efficiency dimension is measured by green total factor productivity (GTFP), the structural dimension is measured by the industrial structure advanced index, and the sustainability dimension is reflected by the carbon emission intensity per unit of GDP. In terms of theoretical mechanism, this study proposes the transmission path of "technological innovation → factor allocation optimization → quality improvement", and assumes that industrial structure upgrading and energy efficiency improvement are the two key intermediary variables connecting green technology innovation and economic growth quality. Specifically, green technology innovation can improve energy efficiency by promoting clean energy substitution and pollution control technology upgrades, thereby reducing factor consumption per unit of output (acting on the efficiency dimension), and at the same time, green technology

innovation can give birth to green industries including energy conservation and environmental protection, new energy, and promote the transformation of industrial structure from high energy consumption to high added value (acting on the structural dimension), and finally jointly achieve the improvement of the quality of economic growth. ”

2.2. Empirical model design

In order to systematically test the mechanism through which green technology innovation affects the quality of economic growth, this study constructs an empirical model in three steps to verify the direct effect, mediating effect and moderating effect in turn, and ensures the reliability of the conclusion through endogenous treatment and robustness test.

2.2.1. Benchmark regression model: test direct effects

Firstly, a two-way fixed-effect model (FE) is constructed to investigate the direct impact of green technology innovation on the quality of economic growth, and to control the individual heterogeneity and macro time trend of provinces. The bidirectional fixed effect model is specifically shown in Formula (1).

$$GrowthQuality_{it} = \alpha_0 + \beta_1 GreenTech_{it} + \gamma \sum Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

Among them, i represents the province ($i=1,2,...,30$), t represents the year ($t=2011, 2012,...,2023$); The dependent variable, $GrowthQuality_{it}$, is the provincial-level index for economic growth quality. It is calculated using the entropy method through the three-dimensional index system of "efficiency-structure-sustainability" (green total factor productivity, industrial structure upgrading index, carbon intensity), and the core explanatory variable $GreenTech_{it}$ is the level of green technology innovation, measured by the number of green patents granted. $Controls_{it}$ is a set of control variables, including $MarketIndex$, $GovTech$, μ_i is the fixed effect of the province, λ_t is the fixed effect of time, and ε_{it} is the random perturbation term.

2.2.2. Mediation effect model: test the conduction pathway

Based on the theoretical assumption, industrial structure advancement ($IndStruct$) and energy efficiency improvement ($EnergyEff$) are the key mediating variables affecting the quality of economic growth by green technology innovation. The total effect test model is shown in Formula (2), the mediator variable test model is shown in Formula (3), and the joint test model of direct effect and mediator effect is shown in Formula (4).

$$GrowthQuality_{it} = \alpha_1 + \beta_2 GreenTech_{it} + \gamma_1 \sum Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

(Total effect test, the core item of the same benchmark model)

$$M_{it} = \alpha_2 + \beta_3 GreenTech_{it} + \gamma_2 \sum Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

(Mediation variable test, M stands for $IndStruct$ and $EnergyEff$, respectively)

$$GrowthQuality_{it} = \alpha_3 + \beta_4 GreenTech_{it} + \delta M_{it} + \gamma_3 \sum Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (4)$$

(Joint test of direct effect and mediating effect)

By testing the significance of β_2 , β_3 and δ , combined with the Bootstrap method (500 repeated sampling), the mediating effect was judged whether it was true, and the ratio of the mediating effect to the total effect ($\delta \times \beta_3 / \beta_2$) was calculated to distinguish the difference between the core mediator and the supplementary mediator.

2.2.3. Moderating effect model: testing the moderating effect of digital infrastructure

In order to investigate the moderating effect of digital infrastructure (Digital, measured by Internet penetration rate, Internet broadband access subscribers (10,000 households) / permanent residents (10,000 people) at the close of the year) on the relationship between "green technology innovation and economic growth quality", the interaction terms of core explanatory variables and moderating variables are introduced into the benchmark model, and the moderating effect model incorporating the interaction term of digital infrastructure is shown in the following formula (5).

$$GrowthQuality_{it} = \alpha_4 + \beta_5 GreenTech_{it} + \beta_6 Digital_{it} + \beta_7 (GreenTech_{it} \times Digital_{it}) + \gamma_4 \sum Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (5)$$

Among them, $GreenTech_{it} \times Digital_{it}$ are interactive terms, and the core concern is the symbol and significance of the coefficient β_7 : if β_7 is significantly positive, it means that digital infrastructure enhances the role of green technology innovation in promoting growth quality; If it is significantly negative, it indicates that the short-term resource allocation imbalance weakens the facilitating effect.

2.3. Data and variables

The sample of this study is panel data from 30 provincial-level administrative regions in China covering the period 2011-2023 (excluding Tibet, due to missing data from some years). The interpreted variable is GrowthQuality, which is objectively weighted by entropy method to synthesize the comprehensive index. The calculation steps are as follows: firstly, the original data of the three indicators are standardized min-max to eliminate the dimension, the proportion of each index in each sample is calculated, and then the entropy value and difference coefficient are calculated in accordance the principle of information entropy, and finally the weight of each index is determined according to the difference coefficient, and the comprehensive index of economic growth quality is weighted to synthesize. The higher the index value, the better the economic growth quality of the corresponding province. The explanatory variable is GreenTech, measured by the number of green patent authorizations. The moderating variable is digital infrastructure (Digital), and the proportion of Internet broadband access users to the permanent population at the end of the year (i.e., Internet penetration rate) reflects its development level. The control variables include MarketIndex, GovTech, to exclude other interfering factors. The research data mainly comes from public data released by the National Bureau of Statistics of the People's Republic of China, the China Research Data Service Platform (CNRDS) and the annual China Statistical Yearbook [10-12].

2.4. Inspection system

To secure the reliability of the research conclusions, this study has been rigorously tested from many aspects. The endogenousness of this study mainly comes from bidirectional causality and omission variables. Two-way causality denotes that green technology innovation promotes the quality of economic growth, and high-quality growth may also feedback R&D investment, and the missing variables include factors that are difficult to quantify such as regional innovation culture. To this end, this study selects GreenTechit's lag period 1-2 (L1_GreenTech, L2_GreenTech) as the instrumental variable, uses the two-stage least squares method (2SLS) estimation, and tests the weak instrumental variable problem through the first stage F statistic (>10) to ensure that the estimation is unbiased, and at the same time satisfies the hypothesis of instrumental variable correlation and exogenousness. The robustness test is realized by "substituting the core variable measurement method", replacing the measurement index of GreenTech from "green patent authorization" to "green patent filing", repeating the benchmark regression and moderating effect regression, and at the same time performing the Bootstrap test again on the mediating effect, if there is no substantial change in the sign and significance of the core coefficients (β_1 , β_7 , and the proportion of mediating effects), it proves that the conclusion is robo. In addition, in order to further explore regional differences, this study also conducted a heterogeneity analysis, and investigated the differences in the moderating effects of digital infrastructure in different regions by regressing three samples in the east, central and west.

3. Results

Regarding the direct effect and the role of government, benchmark regression shows that the direct effect of green technology innovation on the quality of economic growth is not significant ($\beta=-6.49e-07$, $P=0.584$), which is different from the theoretical expectation, but it has important policy implications, and the promotion of green technology innovation on the quality of economic growth is not a simple and immediate direct relationship. This preliminarily verifies the problems of "lagging in transformation" and "market failure" proposed in the introduction, that is, there is a cycle from R&D to economic performance of green technology, and it may appear as a cost burden due to resource crowding in the early stage. At the same time, government science and technology expenditure significantly positively affects the quality of growth at the 1% level ($\beta=0.0002075$, $P<0.001$), indicating that the government plays an indispensable key role in promoting R&D and diffusion of green technologies, especially in making up for market failures. The R^2 in the model group is 0.6881, and the time and individual fixation effects are significant, indicating that the model setting is reasonable and can better explain the change in the quality of economic growth.

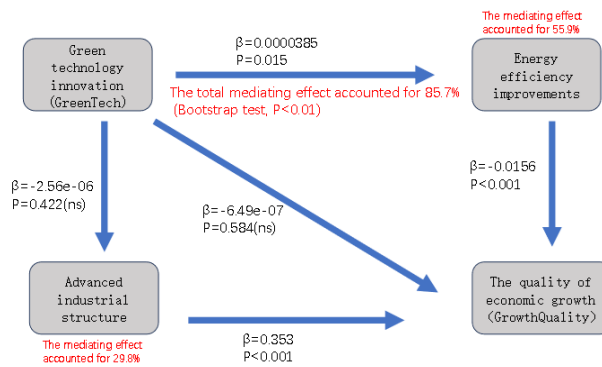


Figure 1. Green tech innovation, energy efficiency & industrial structure: mediating effect on economic growth quality

Figure 1 shows the mediating mechanism of green technology innovation affecting the quality of economic growth, and the results show that it is mainly indirectly promoted by the upgrading of industrial structure (29.8%) and energy efficiency improvement (55.9%) (total mediating effect accounts for 85.7%, $P < 0.01$). Specifically, green technology innovation significantly improves energy efficiency ($\beta = 0.0000385$, $P = 0.015$), and because carbon intensity is a negative-oriented indicator, its significantly negative coefficient ($\beta = -0.0156$, $P < 0.001$) indicates that the improvement of energy efficiency significantly positively affects the quality of economic growth and forms a complete transmission chain. While the upgrading of industrial structure can directly enhance the quality of economic growth ($\beta = 0.353$, $P < 0.0001$), green technology innovation does not have a significant effect on its direct promotion ($P = 0.422$), so the mediating role is limited.

Regarding the moderating effect, the digital infrastructure measured by internet penetration in this study significantly and negatively moderates the relationship between green technology innovation and economic growth quality, and this finding remains robust when using the substitution variable and instrumental variable methods.

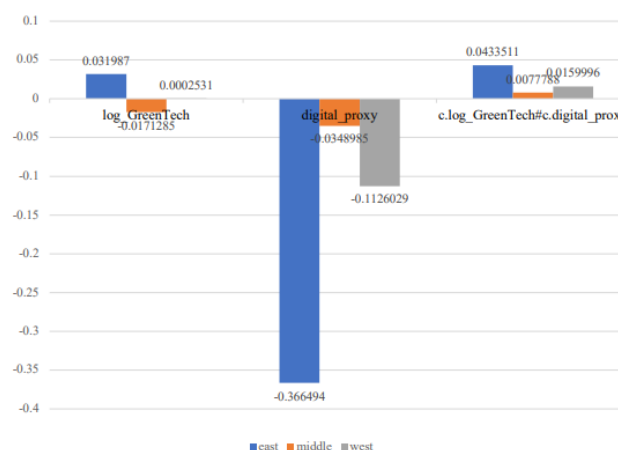


Figure 2. Regional differences in green tech innovation, digital infrastructure and their interaction on economic growth quality

Figure 2 shows that green technology innovation ($\log_GreenTech$) is significantly positive only at the 1% significance level in the eastern region ($\beta = 0.031987$, $P < 0.01$), which can significantly promote

the quality of growth, while it is significantly negative at the 1% significance level in the central region ($\beta=-0.0171285$, $P<0.01$), and has no significant impact in the western region ($P=0.975$). Digital infrastructure (digital_proxy) had a negative impact in both the east and west, with a significant negative height in the east ($\beta=-0.366494$, $P<0.001$), a significant negative level near 10% in the western region ($\beta=-0.1126029$, $P=0.087$), and no significant impact in the central region ($P=0.416$). The interaction term (c.log_GreenTech#c.digital_proxy) only showed a positive effect in the east and west, with a high degree of significance in the east at the 1% level ($\beta=0.0433511$, $P<0.001$), a significant margin in the western part of the 10% significance level ($\beta=0.0159996$, $P=0.069$), and no significant effect in the middle ($P=0.134$). It reflects that the synergy between green technology and digital infrastructure in the central and western regions has not yet been formed.

In order to alleviate the endogenous problem of core variables, this paper uses 2SLS regression and selects "lagging green patent grants for 1-2 phases" as the instrumental variable (sample size 330), and the results further support the benchmark conclusion. In the first stage, the F statistic is between 452.65 and 946.57, which is much higher than the critical value of 10, and there is no weak instrumental variable problem. The P value of the Wald-chi2 statistic of the model was 0.0000, and the overall height was significant, and the R^2 was between 0.8855 and 0.9066, and the fitting effect was good. The coefficient of green technology innovation (greenpatent/greentech) was still insignificant (greenpatent: $\beta=-5.02e-06$, $P=0.094$; greentech: $\beta=-9.92e-06$, $P=0.342$), which was consistent with the conclusion that the direct effect was not significant. The interaction term (greenpatent_dig~r) was significantly positive ($t=1.94$, $P=0.052$) near 5%, which verified the robustness of the moderating effect. The industrial structure advancement (indstruct) was significantly positive in all models (e.g., $\beta=0.3882$, $t=22.88$, $P<0.001$), which further confirmed the positive effect of industrial optimization on growth quality and echoed the conclusion of the mediating effect. The Hausman test showed that $\chi^2(4)=24.78$ ($P<0.001$) supported the use of a fixed-effect model to exclude individual heterogeneity interference.

After replacing the green technology innovation measurement index from "green patent authorization" to "green patent application" in the robustness test, the direct effect was not significant at the 95% confidence level ($\beta=-5.02e-06$, $P=0.094$), and there may be a weak negative effect, which was consistent with the conclusion of benchmark regression ($\beta=-6.49e-07$, $P=0.584$), which further verified the stability of the direct effect was not significant.

Table 1. Robustness test results of core variables

Variable	Coefficient	$P> z /P> t $	Conclusion
Greenpatent	-5.02e-06	0.094	Marginal negative impact (close to 10% significant)
Greenpatent_digital_inter (Interaction between green patents and digital infrastructure)	0.0000135	0.052	Marginal positive impact (close to 5% significant)
Marketindex	0.0111048	0.000	Significant positive impact($P<0.001$)
indstruct	0.3881783	0.000	Significant positive impact($P<0.001$)
L1_green,patent	1.916339	0.000	Significant positive impact($P<0.001$)
L2_greenpatent	-1.063469	0.000	Significant negative impact($P<0.001$)

Table 1 shows that the core interaction item `greenpatent_digital_inter` the marginal positive impact is stable (close to 5% significant), indicating that the interaction between digital technology and green patents has a robust effect on the promotion of growth quality. The significance and direction of the control variables `marketindex`, `instruct` and the lagging term of the first phase of the green patent are consistent with the direction, which further verifies the reliability of the model. In summary, the core conclusion of this paper is still valid after the variable and model adjustment, which is relatively roable.

4. Discussion

The promotion of the quality of economic growth by green technology innovation is mainly based on "indirect transmission", and energy efficiency improvement is the core intermediary path, which achieves the dual growth of "efficiency + green" by reducing the cost of high-energy-consuming industries and alleviating environmental constraints. The upgrading of industrial structure is an important supplementary path, providing application scenarios for green technology, and the two jointly contribute more than 80% of the effect. The direct effect has not yet appeared due to lagging transformation and market failure, and the direct empowerment ability still needs to be released, which echoes the realistic background of "the current role of green technology innovation in promoting the quality of economic growth has not yet been fully released" in the introduction.

It is worth noting that this study finds that digital infrastructure has a significant negative regulation on the relationship between "green technology innovation and economic growth quality", which is still stable after being tested by the substitution variable and instrumental variable method, and the underlying reasons can be analyzed from two aspects: short-term resource allocation imbalance and insufficient technology adaptability. From the perspective of resource allocation, digital infrastructure construction requires a large amount of energy-consuming resources in the short term, which may crowd out the green technology research and development budget, and its own high-carbon characteristics will also offset the emission reduction effect of green technology. Based on data from the China Tower Research Institute, the current energy consumption of a single 5G device stands at 3~5kW, 2~3 times that of 4G devices. Meanwhile, infrastructure projects like 5G base stations and large-scale data centers are highly reliant on high-carbon emission industries—for instance, a single 5G base station consumes an average of 8.5 tons of steel, and a single 1000kV UHV AC project requires approximately 2000 tons of high-magnetic induction grain-oriented electrical steel. This high-energy-consumption and high-carbon investment and construction model directly increases regional carbon emission intensity and undermines the positive effect of green technology innovation on the quality of economic growth [13]. From the perspective of technological adaptability, the integration of digital infrastructure and green technology in most regions is still in the "basic connection" stage and has not yet crossed the "technology maturity threshold". This aligns with the findings of Ozturk et al., who identified a nonlinear impact of technology on resource management [14]. Through an analysis of panel data from 1990 to 2021 covering 13 resource-based economies, they pointed out a long-term inverted U-shaped relationship between technology investment (TI) and trade-adjusted resource management indicators (MFPs). Specifically, initial technology investment drives the expansion of resource exploitation scale and increases MFPs, which is analogous to the high energy consumption observed in the early development stage of digital infrastructure. The essence of the current negative regulation of digital infrastructure on green technology is that it has not yet broken through the "technology integration threshold", and its resource consumption effect is still greater than the synergy effect.

Government and market synergy is the key support for improving the quality of growth. On the one hand, government science and technology spending can make up for the market failure of green

technology innovation by subsidizing green research and development and improving infrastructure. On the other hand, a perfect market mechanism can optimize resource allocation and guide capital flow to the integration of green technology and digital infrastructure. The two jointly provide guarantee for the implementation of green technology and the improvement of growth quality. Furthermore, the moderating effect of green technology innovation and digital infrastructure exhibits significant regional heterogeneity. Green technology innovation exerts a positive effect on growth quality only in the eastern region, a negative effect in the central region and no significant effect in the western region. Meanwhile, digital infrastructure shows negative moderating effects only in the eastern and western regions, and no significant effect in the central region.

5. Conclusion

Through empirical analysis, this study demonstrates that green technology innovation primarily promotes the quality of economic growth indirectly through two intermediary paths: industrial structure optimization and energy efficiency improvement. It is worth noting that digital infrastructure itself exerts a direct positive impact on the growth quality, but it plays a negative moderating effect in the relationship between green technology and growth quality. Market-oriented indices and government investment in science and technology have also played an important role in improving the quality of growth. In addition, significant regional heterogeneity was found, with the strongest comprehensive effect in the eastern region and negative effects in the central region.

Drawing on the above conclusions, this paper proposes the following recommendations: at the national level, a special green technology transformation fund should be set up, a green technology bank should be developed, and the green patent protection mechanism should be improved, so as to promote the upgrading of the industrial structure. At the regional level, policies should be focused. The eastern region should give full play to its digital infrastructure advantages. For the central region where the negative effect of green technology innovation occurs, policies should focus on optimizing the technology introduction structure and avoiding the lock-in of low-end technology paths. While making up for the shortcomings of digital infrastructure, policies for the western region need to focus on promoting the in-depth application of digital technology in the green transformation of advantageous industries such as automobiles and electronics. At the enterprise level, they should increase the intensity of green R&D investment and strengthen industry-university-research cooperation to accelerate technology transformation. At the government level, policy formulation needs to focus on synergy with green technology development, avoid excessive tilt of resources to the digital field, optimize the structure of fiscal expenditure, and increase green finance support.

This study has certain limitations, mainly reflected in the fact that it only analyzes the moderating effect of digital infrastructure from the provincial macro level, and fails to cover the micro level of enterprises and the synergy effect of the international industrial chain. At the same time, there is still room for optimization in variable selection and model setting, and more influencing factors can be considered in subsequent studies.

In addition to cross-border comparative research, the future research direction will compare and analyze the differences between China and developed countries in Europe and the United States in the path of green technology innovation, and focus on the impact of different policy systems (such as carbon trading mechanisms and green subsidies) on technology transformation efficiency. Secondly, it is also possible to carry out collaborative research on the industrial chain, explore the collaborative application mechanism of green technologies in the upstream and downstream of the industrial chain, and establish a cross-industry technology diffusion model, such as studying the penetration path of new energy technology into traditional manufacturing.

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