

Green Technology Innovation, Carbon Emissions, and High-Quality Development of Manufacturing Firms: Mechanisms and Empirical Evidence

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Abstract: High-quality development of enterprises is a critical issue in China's pursuit of a modern development paradigm. Against this backdrop, green technology innovation plays a vital role in achieving carbon reduction targets and promoting high-quality development. Focusing on the pathways through which green technology innovation drives high-quality development in manufacturing firms, this study constructs an analytical framework of "green technology innovation—carbon emissions—high-quality development" using data from Chinese listed manufacturing companies from 2015 to 2024. Empirical tests are conducted using baseline regression, mediation effect, and threshold models. The results show that green technology innovation significantly promotes high-quality development in manufacturing firms. Carbon emissions play a positive mediating role, accounting for 56.22% of the total effect. Moreover, the impact of green technology innovation on high-quality development exhibits a single-threshold effect, characterized by an insignificant effect in the early stage and a significantly strengthened effect in the later stage. Accordingly, policy recommendations are proposed, including strengthening innovation support and providing differentiated policy provisions.

Keywords: Green technology innovation; High-quality development of manufacturing firms; Carbon emissions.

1. Introduction

Under the dual pressures of global warming and continued ecological degradation, carbon emissions from the manufacturing sector have reached 70% of global industrial carbon emissions, making manufacturing a primary source of emissions. The green transformation of manufacturing and high-quality economic development have become global consensus. As a major manufacturing country, China's manufacturing industry serves as a pillar of the national economy. In 2025, the value added of manufacturing accounted for 27.8% of GDP, yet energy intensity per unit of output remains 1.8 times that of developed countries. There is an urgent need to achieve the dual carbon goals and high-quality development through green technology innovation. This study systematically reviews the current state of research on manufacturing carbon emissions and high-quality development, reveals the underlying mechanisms, and provides empirical evidence to support policy-making and corporate practice.

Existing studies have explored the relationship between green technology innovation and high-quality development from multiple dimensions, but three main gaps remain. First, the transmission pathways among green technology innovation, carbon emissions, and high-quality development have not been sufficiently analyzed, with most studies focusing on direct effects and lacking quantitative validation of mediation mechanisms. [1] Second, the stage-dependent characteristics of the impact of green technology innovation on high-quality development are underexplored, as most studies assume linear relationships without empirically testing nonlinear threshold effects. Third, the practical implications for differentiated policy design remain underdeveloped, with existing research often remaining at the level of general policy recommendations without considering

firm heterogeneity.[2]To address these gaps, this study uses data from Chinese listed manufacturing companies from 2015 to 2024 to empirically investigate the mechanisms through which green technology innovation affects carbon emissions and high-quality development, revealing the mediating role of carbon emissions and the threshold characteristics, thereby optimizing policy design.

The potential contributions of this study are threefold. First, it develops an analytical framework of "green technology innovation—carbon emissions—high-quality development," strengthening the quantitative validation of the mediation mechanism and deepening understanding of the influence pathways of green technology innovation. Second, it empirically tests the positive effect of green technology innovation on high-quality development using baseline regression, mediation, and threshold models, systematically revealing the mechanisms and stage characteristics of this relationship, providing theoretical support and empirical evidence for the green and low-carbon transformation of manufacturing. Third, based on the mechanisms identified, it offers policy recommendations for corporate green transformation to inform future policy-making.

2. Theoretical Analysis and Research Hypotheses

2.1. Direct Effect of Green Technology Innovation on High-Quality Development

Green technology innovation is a key pathway for addressing environmental pollution and enhancing corporate green competitiveness. It promotes high-quality development by driving technological progress, optimizing industrial structures, and improving social welfare. First, it serves as a critical source of total factor productivity growth by introducing advanced green processes and equipment,

shifting the technological frontier, optimizing factor allocation, and promoting resource efficiency. Second, it drives the upgrading of industrial structures. Traditional manufacturing transforms through green technologies, while emerging green industries build new value chains. Third, green technology innovation enhances corporate reputation and long-term financial value by creating green products and processes, reducing costs, and gaining consumer and investor trust. Based on this, Hypothesis 1 is proposed:

H1: Green technology innovation has a significant positive impact on high-quality development in manufacturing firms.

2.2. Green Technology Innovation, Carbon Emissions, and High-Quality Development

In the short term, green technology innovation may have dual effects on carbon emissions and high-quality development, which can be analyzed from environmental and economic benefit perspectives. Environmentally, green technology innovation reduces total energy consumption and improves energy efficiency through technology diffusion and process optimization, lowering carbon intensity. [3] There is a significant “U-shaped” relationship between green technology innovation and carbon emissions, with the emission-reducing effect dominating as innovation levels increase. Economically, green technology innovation promotes the development of green equipment and products, optimizes production configurations, and improves total factor productivity, thereby reducing production costs. However, lower costs may lead firms to expand production in pursuit of profit maximization, potentially increasing total energy consumption and emissions. From the perspective of new structural economics, this increase in emissions may be accompanied by revenue growth, market share expansion, and capital accumulation, forming a transition pathway of “grow first, reduce later.” [4] Thus, the overall short-term impact of green technology innovation on carbon emissions remains uncertain. Accordingly, the following hypotheses are proposed:

H2a: In the short term, green technology innovation reduces carbon emissions and promotes high-quality development in manufacturing firms.

H2b: In the short term, green technology innovation increases carbon emissions and promotes high-quality development in manufacturing firms.

2.3. Threshold Effect of Green Technology Innovation on High-Quality Development

The impact of green technology innovation on high-quality development may exhibit a threshold effect based on its own level, consistent with the technology life cycle. Below the threshold, green technology is in its growth stage, with limited and unstable effects on productivity due to ongoing adaptation and integration. Once the threshold is crossed, the technology enters the maturity stage, characterized by standardization and scale application, with significantly enhanced and stable contributions to quality development. Mature green technologies effectively optimize energy structures and reduce carbon intensity, and integration with digital technologies accelerates their application. Even if technologies eventually enter a declining phase, established firms often maintain innovation levels above the threshold due to competitive pressures and environmental regulations, preventing a decline in effects. Thus, a single-threshold nonlinear effect is expected.

H3: The impact of green technology innovation on high-quality development exhibits a single-threshold effect based on its own level.

3. Research Design

3.1. Model Specification

3.1.1. Baseline Regression Model

To test Hypothesis 1, the following baseline regression model is constructed:

$$HQ_{it} = \alpha_0 + \alpha_1 GTI_{it} + \gamma Control_{it} + \mu_i + \nu_t + \epsilon_{it}$$

where HQ_{it} represents high-quality development, GTI_{it} represents green technology innovation, $Control_{it}$ represents control variables, and μ_i and ν_t denote individual and time fixed effects.

3.1.2. Mediation Effect Model

To test the mediating role of carbon emissions, the following models are specified:

$$C_{it} = \phi_0 + \phi_1 GTI_{it} + \gamma Control_{it} + \mu_i + \nu_t + \epsilon_{it}$$

$$HQ_{it} = \omega_0 + \omega_1 GTI_{it} + \omega_2 C_{it} + \gamma Control_{it} + \mu_i + \nu_t + \epsilon_{it}$$

3.1.3. Panel Threshold Model

To test the nonlinear threshold effect, the following single-threshold and double-threshold models are constructed:

$$HQ_{it} = \theta_0 + \theta_1 GTI_{it} \times I(GTI_{it} \leq \lambda) + \theta_2 GTI_{it} \times I(GTI_{it} > \lambda) + \gamma Control_{it} + \mu_i + \nu_t + \epsilon_{it}$$

3.2. Variable Selection

3.2.1. Core Explanatory Variable

Green technology innovation (GTI) is measured by the number of green patent applications, log-transformed, following existing literature.

3.2.2. Dependent Variable

High-quality development (HQ) is measured by total factor productivity, estimated using the OP method, with the LP method used for robustness checks.

3.2.3. Mediator Variable

Carbon emissions (C) are measured as the total carbon emissions from electricity, coal, liquefied petroleum gas, transportation, and heat consumption, log-transformed.

3.2.4. Control Variables

Control variables include listing age, return on assets, and executive compensation.

4. Empirical Results and Analysis

4.1. Baseline Regression Results

The Hausman test yields a value of 144.59 ($p < 0.01$), indicating that a fixed-effects model is appropriate. Regardless of whether control variables are included, the coefficient for GTI is significantly positive at the 1% level, supporting H1.

4.2. Robustness and Endogeneity Tests

Robustness checks using alternative measures of GTI (green patent grants) yield consistent results. Endogeneity is addressed by lagging the independent variable and using instrumental variable estimation (two-stage least squares). Both approaches confirm the robustness of the findings.

4.3. Heterogeneity Analysis

4.3.1. Firm Size

GTI significantly promotes HQD in both large and small manufacturing firms, with identical coefficients (0.015, $p < 0.01$). However, the model fit is higher for large firms, suggesting greater explanatory power.

4.3.2. Pollution Intensity

GTI has a stronger effect on high-pollution industries (0.043) than on low-pollution industries (0.032), both significant at the 1% level. This may be due to stricter environmental regulations and greater marginal benefits of green innovation in high-pollution sectors.

4.4. Mediation Effect Test

GTI significantly increases carbon emissions, and carbon emissions positively affect HQD. The mediation effect accounts for 56.22% of the total effect, supporting H2b. This reflects a “grow first, reduce later” transition pattern.

5. Threshold Effect Test

A single threshold is identified at a GTI value of 1.386. Below this threshold, GTI has no significant effect on HQD. Above the threshold, the coefficient becomes 0.0224 and is significant at the 1% level, supporting H3. This indicates that GTI must reach a certain maturity level before it can meaningfully drive high-quality development.

6. Conclusion and Policy Implications

6.1. Research Conclusions

Based on data from Chinese manufacturing firms from 2015 to 2024, this study examines the mechanisms, heterogeneity, and threshold effects of green technology innovation on high-quality development. The main conclusions are as follows: First, green technology innovation significantly promotes high-quality development, a finding that remains robust after endogeneity treatment. Second, carbon emissions play a positive mediating role, with a mediation effect proportion of 56.22%. Third, a single-threshold effect exists, with a threshold value of 1.386. Fourth, heterogeneity analysis reveals that GTI benefits both large and small firms but has stronger effects in high-pollution industries.

6.2. Policy Recommendations

6.2.1. Strengthening Support for Green Technology Innovation to Help Firms Cross the Threshold

Governments should establish special funds for green technology innovation, provide tax incentives, and promote green finance products. Industry–academia collaboration should be enhanced to accelerate technology transfer, and service platforms should be developed to support technology adoption.

6.2.2. Implementing Differentiated Policies to Address Firm Heterogeneity

Large firms should be encouraged to lead innovation consortia, while small and medium-sized firms should benefit from simplified subsidy processes and shared technology resources. High-pollution industries should face a combination of regulation and incentives, whereas low-pollution industries should focus on green product development and market cultivation.

6.2.3. Optimizing Carbon Emission Management to Support Transition Periods

A dynamic carbon management system should be established to avoid one-size-fits-all reduction targets, with transitional targets for early-stage transformation. Carbon markets should be expanded to include more small and medium-sized enterprises, and renewable energy and carbon capture technologies should be promoted to shorten the transition period.

6.2.4. Establishing a Multi-Stakeholder Governance Framework

Government–enterprise collaboration should be strengthened through green procurement and market incentives. Internal corporate mechanisms, such as green innovation performance assessments, should be introduced. Regional and industry coordination should be enhanced to narrow development gaps and foster a governance structure involving government, enterprises, markets, and industry associations.

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