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Review Article

Examining the Influence of FinTech on Manufacturing's Low-Carbon Transition: Unveiling the Mediating and Moderating Pathways

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Abstract: As global climate concerns intensify alongside China's pursuit of carbon neutrality, the low-carbon transition of the manufacture industry has become an urgent necessity. As a key driver in the digital era, how FinTech can effectively facilitate this transition has emerged as a critical issue. Therefore, this study selects panel data from 30 Chinese provinces spanning 2004 to 2023 to examine the mechanisms through which FinTech influences low-carbon development of manufacture industry. The study shows: (1) FinTech exerts a direct promoting effect on the low-carbon development of the manufacture industry, but this effect is only significant in regions with high levels of FinTech. (2) FinTech indirectly facilitates low-carbon transformation through stimulating green technology innovation and reducing energy intensity. (3) Government environmental attention and human capital exhibit stage-specific moderating roles along the transmission pathway, the former amplifies FinTech's driving force on technological innovation, whereas the latter accelerates the conversion efficiency of innovation outcomes. Building upon these findings, this study proposes the following targeted policy recommendations: regions with underdeveloped financial infrastructure should promote the integration of FinTech with traditional financial services; green technology innovation should be strengthened through dedicated funds, while energy efficiency should be enhanced via integrated "energy-efficiency loans with digital management systems"; government should build a phased and multi-party collaborative policy system, combining stronger policy guidance at the front end with enhanced cultivation of interdisciplinary talent at the back end, ultimately forming a comprehensive support system. This research elucidates the dual pathways and conditional mechanisms through which FinTech drives low-carbon development in manufacturing, offering strategic insights for aligning technological innovation, financial support, and policy guidance.

Keywords: FinTech, Low-Carbon Development of Manufacture Industry, Green Technology Innovation, Government Environment Attention, Mediating Effects.

1. INTRODUCTION

In the process of global development, urbanization and industrialization have driven rapid economic growth while simultaneously posing formidable environmental challenges (Zhao and Zhang, 2025). Environmental issues transcend national borders, necessitating collaborative global responses, with widespread consensus on low-carbon transition among nations. The 2015 United Nations-adopted "2030 Agenda for Sustainable Development" explicitly outlines specific goals such as addressing climate change and promoting clean energy, providing a clear direction for global low-carbon transformation (Han and Wang, 2025). As a major contributor for energy consumption and carbon emissions, manufacturing plays a pivotal role in this transition (Liu *et al.*, 2025b). Promoting green transformation in manufacturing not only alleviates climate pressure but also enhances industrial competitiveness, achieving a balance between development and environmental protection. Therefore, investigating the pathways and mechanisms of low-carbon transition in manufacturing holds significant implications for policy formulation and practical implementation.

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As the world's second-largest economy, China has been the largest carbon emitter in terms of total carbon emissions since 2007 (Tang *et al.,* 2020) and has also ranked first in global energy consumption since 2010 (Ma *et al*., 2019). In addressing global climate change and to honor its commitments to the international community, the Chinese government committed in 2009 to achieve a 40%-45% reduction in carbon intensity from 2005 levels by 2020 (Zhou *et al*., 2019). Manufacturing constitutes the cornerstone in China's industrial structure and accounts for the largest share of national energy consumption. In 2020, the Chinese manufacturing sector's energy consumption stood at 2,797 million tons of standard coal (56.1% of the national total), making it the source of 6,946 million tons of carbon dioxide emissions, which accounted for 70.2% of the country's total (Ma *et al*., 2025). Guided by the dual carbon strategic objectives, promoting the low-carbon transition of the manufacturing sector has become an imperative for China to achieve green development.

As a significant outcome of the Fourth Industrial Revolution, FinTech has effectively driven energy system transformation through innovative financing models (Dong and Yu, 2024). It expands financing channels for low-carbon projects (Teng and Shen, 2023), reduces capital costs, and diversifies investment risks (Zhou *et al*., 2025), thereby fostering the development of the green energy projects and providing critical support for manufacturing sector's low-carbon transition (Tao, 2025). FinTech accelerates the integration of technology and financial services, with increasing internet penetration, user acceptance of innovative technologies continues to rise (Wang *et al*., 2020b). It plays a pivotal role in broadening financial service coverage, reducing service costs, and enhancing service efficiency (Lange *et al*., 2020). Concurrently, FinTech promotes clean energy utilization by optimizing resource allocation, contributing to reduced energy intensity and carbon emissions, thus advancing green transformation in manufacturing (Elheddad *et al*., 2021). Therefore, FinTech not only directly supports low-carbon development in manufacturing through financing but may also generate indirect facilitating effects by fostering green technology innovation and lowering energy intensity, a mechanism that warrants further investigation.

Additionally, the contribution of FinTech to low-carbon manufacturing is also mediated by the level of government environmental concern and the availability of human capital (Yuan *et al*., 2025b; Chen *et al*., 2025a). On one hand, heightened government attention to environmental issues can strengthen central environmental oversight and foster public environmental participation, thereby advancing environmental sustainability (Sun *et al*., 2025). On the other hand, high-quality human capital, through its professional competence and innovative capabilities, provides a continuous driving force for low-carbon technological innovation in manufacturing (Chang *et al*., 2024).

This study addresses the following research questions:

1. Does FinTech promote low-carbon development in manufacture industry?
2. Is the promoting effect related to the extent of FinTech development?
3. Does FinTech promote low-carbon development in manufacture industry through green technology innovation?
4. Does FinTech promote low-carbon development in manufacture industry through reducing energy intensity?
5. How do government environmental attention and human capital function in the process of FinTech promoting low-carbon development in manufacture industry?

The contributions and innovations of this study are as follows:

Firstly, this paper develops a comprehensive theoretical framework incorporating direct effects, mediating effects (green technology innovation and energy intensity), and moderating effects (government environmental attention and human capital). This framework unravels the complex mechanisms through which FinTech promotes low-carbon development in manufacture industry, thereby filling a gap in existing theory regarding an integrated explanation of issues in this field.

Secondly, this study reveals that government environmental attention and human capital exert stage-specific and asymmetric moderating effects along the "FinTech → green technology innovation → low-carbon development" mediating chain. Specifically, government attention strengthens the front-end drive for technological innovation, while human capital ensures the back-end efficiency of technology transformation. This finding thereby refines the synergistic theory of institutions and talent in green transitions.

Thirdly, this paper reveals a Matthew Effect in FinTech's role in promoting low-carbon development in the manufacture industry, where regions with higher FinTech levels exhibit more pronounced promotional effects. This finding clarifies the spatial heterogeneity in FinTech's enabling impact and provides key empirical basis for formulating regionally differentiated digital finance policies.

2. LITERATURE REVIEW AND RESEARCH HYPOTHESIS

2.1 FinTech and Low-Carbon Development of Manufacture Industry

FinTech is an emerging field born from the fusion of finance and technology. Here, core innovations like artificial intelligence, big data, and blockchain are applied to transform or optimize established financial services. Its objectives center on innovation in financial products, services, and business models, achieved by boosting efficiency, cutting costs, and refining the user experience (Yan *et al*., 2022). By applying digitalization and environmentally friendly production technologies, FinTech empowers manufacturers to pursue green innovation, resource optimization, and carbon reduction, thereby advancing their sustainable development goals (Li *et al*., 2024a).

Powered by technological innovation in the digital economy, FinTech has become a major catalyst for global economic growth and plays a critical role in advancing China's high-quality development (Tang *et al*., 2023). The relationship between FinTech and the environment, however, is one of dual nature. Positively, it supports climate action by facilitating green energy trading, improving carbon market mechanisms, and broadening climate finance (Najaf and Seera, 2025); negatively, its high energy consumption in operations and rapid depletion of scarce resources have raised sustainability concerns (Tao *et al*., 2022). Empirical evidence remains divided: Wang *et al*., (2020a) observed that FinTech development in G7 countries intensified energy consumption and carbon emissions, whereas Teng and Shen (2023) empirically demonstrated that governments should steer FinTech toward achieving carbon neutrality goals.

At the theoretical level, there is a stronger inclination to support the potential of FinTech in facilitating low-carbon transformation. According to the Innovation Diffusion Theory, as a technologically innovative force with extensive permeability, FinTech fundamentally alters the decision-making behaviors of firms and consumers by transforming traditional payment, credit, and investment systems, thereby driving the socioeconomic system towards a low-carbon trajectory (Guang and Siddik, 2023). The Ecological Modernization Theory posits that the green financial ecosystem constructed on the basis of digital infrastructure can promote cleaner production technologies and facilitate resource recycling, minimizing environmental impacts (Hasan *et al*., 2024). Systems Theory views the economic, technological, and environmental subsystems within a city as deeply interconnected (Zeng and Jiang, 2025). Under this framework, FinTech is regarded as a cross-cutting force that bridges the financial system, technological development, and environmental governance. By improving the availability of green funding, FinTech enables investments in environmental technologies and projects, while its data-driven tools boost transparency and improve decision-making for industrial energy management.

Multiple empirical studies have also validated the low-carbon effects of FinTech. Najaf and Seera (2025) based on data from U.S. listed companies spanning 2010-2022, compared 48 FinTech firms with 145 traditional enterprises and found that FinTech companies exhibited significantly lower carbon footprints. Demonstrating FinTech's role in curbing emissions, Li *et al.*, (2024b) drew on data from six major manufacturing economies (2000-2021) analyzed via a GMM-PVAR model. Analyzing a dataset of 280 Chinese cities (2006-2019), Li *et al*., (2025) identified an inverted U-shaped curve in the FinTech-emissions nexus. This trajectory is characterized by an initial rise in emissions due to technological deployment, followed by enduring reduction effects. The low-carbon transformation driven by FinTech, as reported by Javed *et al.*, (2024), is attributed to gains in economic efficiency and the directing of capital toward green investments, based on their analysis of ten resource-dependent countries (1995-2022). While a robust link exists between FinTech and broad environmental sustainability, how this translates to sustainability practices within individual manufacturing firms has yet to be fully understood. Based on the foregoing analysis, the following assumption is advanced:
H1: *FinTech promotes low-carbon development of manufacture industry.*

2.2 FinTech, Green Technology Innovation and Low-Carbon Development of Manufacture Industry

Corporate green technology innovation represents a strategic initiative to achieve a nation's long-term sustainability goals (Zhao *et al*., 2024). As a core pathway for firms to accumulate intellectual capital, technological investment directly determines their capacity to overcome environmental technology barriers. Research by Guo and Hu (2025) demonstrates that increasing corporate technological investment enhances green technology innovation capabilities. While financing constraints in reality often hinder corporate investment in technology, innovative FinTech services including P2P lending, crowdfunding, and online wealth management provide strong support for green innovation. They achieve this by alleviating funding pressures, lowering costs, and diversifying capital channels (Zhou *et al.*, 2025). This process not only reinforces the positive cycle between technological investment and green innovation but also highlights the enabling role of FinTech in promoting sustainable development.

FinTech plays a pivotal role in advancing the low-carbon transformation of the manufacturing sector by strengthening corporate green technology innovation. This influence operates through two primary channels. (1) FinTech alleviates financial constraints for businesses by restructuring capital market infrastructure and credit evaluation methods, thus directly addressing funding pressures and boosting investment in green innovation and sustainable production (Wang *et al*., 2025a). At the organizational level, it employs technology integration and data-driven methods to boost managerial efficacy in strategy, risk management and resource use. This unlocked efficiency is critical for fostering green technology innovation (Ferri *et al*., 2025). (2) Green technology innovation itself acts as a core driver of manufacturing decarbonization. Its breakthroughs in advancing clean energy, efficiency, and pollution control, directly bolsters the manufacturing sector's progress toward low-carbon development (Dai *et al*., 2025).

Numerous scholars also support the positive impact of FinTech on green technology innovation. Through an empirical analysis of Chinese listed companies (2011-2023), Wang *et al*., (2025) established that FinTech significantly boosts green technology innovation, acting primarily through the channels of improved managerial competence and alleviated financing constraints. Javed *et al*., (2024) utilizing data from ten mineral resource-rich countries over the period 1995-2022, confirmed that sustained progress in green technology innovation effectively promotes carbon emission reduction, whereas stagnation or regression significantly exacerbates emission issues, highlighting the urgency of continuous R&D investment. Zhao *et al*., (2024) constructed a multi-driver model using data from Chinese A-share firms from 2008-2022, demonstrating that environmental investment significantly fosters green technology innovation. In summary, existing research clearly indicates that FinTech facilitates the allocation of more corporate resources toward green technology R&D by easing financing constraints, ultimately driving socioeconomic green transformation. Yet, research on the precise mediating role of green technology innovation in the FinTech-manufacturing low-carbon development nexus remains limited. Based on the foregoing analysis, the following assumption is advanced:
H2: *FinTech promotes low-carbon development of manufacture industry through green technology innovation.*

2.3 FinTech, Energy Intensity and Low-Carbon Development of Manufacture Industry

Energy intensity (energy consumption per unit of GDP) serves as a core indicator for assessing national energy efficiency and the progress of low-carbon transition (Li *et al*., 2025b). In the manufacturing sector, this metric directly determines industrial carbon emission levels. Marra *et al*., (2024) highlighted that low energy intensity facilitates green transformation, while high energy intensity exacerbates environmental burdens. As a critical component of digital technology, FinTech provides essential support for firms to reduce energy intensity through technological innovation and business model restructuring (Li and Yue, 2024).

FinTech reduces energy intensity through two key pathways: The first mechanism lies in its ability to address funding shortages in manufacturing's low-carbon shift by leveraging innovative financial frameworks (Teng and Shen, 2024). For instance, financial instruments such as blockchain-enabled green bonds not only provide low-cost funding for green technology R&D but also mitigate investment risks in renewable energy projects through technologies like smart contracts, thereby channeling more capital into low-carbon technology domains (Zhou *et al*., 2025). Second, FinTech optimizes energy management through digital technologies (Sreenu, 2024). Energy monitoring systems based on big data and artificial intelligence can analyze real-time energy consumption data of production lines and dynamically optimize production processes and energy usage strategies (Yang and Cui, 2025), directly improving corporate energy efficiency and consequently reducing energy intensity.

Numerous empirical studies have also confirmed the positive impact of FinTech on reducing energy intensity. Research by Wu *et al.*, (2025) establishes a robustly positive link between FinTech and progress in decarbonizing the urban energy mix across 278 Chinese cities. Research by Fan *et al*., (2024) based on a provincial panel (2013-2021) from China established a causal link between FinTech development and reduced fossil energy dependence. Chen *et al*., (2025b) further revealed, through provincial panel data from China over 2008-2022, that FinTech decreases electricity consumption intensity. It is noteworthy that scholarly attention has been primarily directed toward the broad, system-wide effects of FinTech on the energy landscape (Wu *et al*., 2025; Gyimah and Bonzo, 2025; Yang and Cui, 2025), whereas the specific micro-level mechanisms of its effects in subsectors such as manufacturing remain underexplored and warrant further investigation. Based on the foregoing analysis, the following assumption is advanced:
H3: *FinTech promotes low-carbon development of manufacture industry through energy intensity.*

2.4 FinTech, Government Environmental Attention and Low-Carbon Development of Manufacture Industry

Government environmental attention, which functions as a key metric of governmental commitment to ecological and environmental preservation, not only embodies the strategic orientation of environmental governance but also directly reflects the prioritization of policy resource allocation. The extent of government attention to environmental issues may influence multiple critical domains, including guiding corporate environmental behavior (Wang and Lei, 2021), advancing carbon reduction strategies (Zhu *et al*., 2023), and fostering green technology innovation (Chen *et al*., 2022).

Unlike environmental regulations and incentive policies, environmental concern focuses more on reflecting the government's depth of understanding and emphasis on environmental governance. Its mechanism of action is mainly reflected in two aspects: firstly, it demonstrates the government's support for sustainable development through direct financial investment, specifically manifested in targeted investments in green infrastructure, environmental monitoring networks, and low-carbon technology research and development (Yang *et al*., 2024). The second is to establish the priority of environmental governance through policy texts and administrative guidelines, and incorporate ecological goals into the core agenda of government work (Yuan *et al*., 2022b). Through theoretical analysis, Wu *et al*., (2025) posited that the policy emphasis local governments place on environmental issues shapes the flow of financial resources, thereby advancing sustainable environmental development.

Multiple empirical studies have confirmed the low-carbon efficacy of government environmental attention. Through a DID model applied to 260 Chinese cities (2006-2023), Yuan *et al*., (2025b) found that regions with high government environmental attention experienced significantly greater improvements in environmental performance through low-carbon policy implementation. The underlying mechanism lies in how heightened government attention strengthens policy enforcement and enhances resource allocation efficiency. Yuan *et al*., (2025a), using Chinese listed companies as research samples from 2010-2022, demonstrated that government environmental attention effectively promotes corporate green technology innovation and drives industrial sustainable development. Yu *et al*., (2025), through spatial econometric analysis of prefecture-level city data in China from 2008-2020, revealed that government environmental attention significantly accelerates the green transformation of energy structures, improves resource utilization efficiency, and reduces carbon intensity. Zhu *et al*., (2024) based on quantitative analysis of data from Chinese manufacturing-listed companies between 2012-2021, found that a 1% increase in government environmental attention corresponds to a 0.1514% rise in corporate carbon reduction efforts. Based on the foregoing analysis, the following assumption is advanced:
H4: *Government environmental attention promotes low-carbon development of manufacture industry.*

Government environmental attention serves as a critical institutional factor influencing the efficacy of FinTech, as it delineates the policy foundation and implementation conditions for low-carbon transition, directly shaping the performance outcomes of FinTech applications (Zeng and Jiang, 2025). The 2023 Central Financial Work Conference explicitly emphasized that finance, as a vital component of the national economy and a core element of national competitiveness, necessitates accelerated development into a financial powerhouse supported by FinTech (Jiao *et al*., 2021). Given the Chinese government's unique capacity for periodic and in-depth intervention in financial markets, along with its dominant role in allocating financial resources, it is reasonable to infer that the priority assigned to environmental issues by local governments will significantly influence the allocation of financial resources toward sustainable environmental development (Wu *et al.*, 2025).

From an institutional theory perspective, governments play a decisive role in the effective utilization of FinTech by formulating supportive policies, constructing regulatory frameworks, and refining accountability mechanisms. Studies confirm that cities where environmental governance is more robust demonstrate a marked tendency to favor sustainable initiatives and green financing. These cities also leverage public-private partnerships to enhance FinTech's role in advancing low-carbon goals (Abu *et al.*, 2024). Regarding underlying mechanisms, applying a threshold model to Chinese data (2010-2020), Liao (2025) found that government attention significantly shapes how FinTech influences green technology innovation. Meanwhile, Chen *et al*., (2025a) through textual analysis of listed company data from 2003-2020, revealed that government environmental attention effectively stimulates corporate green investment behavior by expanding green credit supply and intensifying environmental supervision, thereby driving low-carbon development in the manufacture industry. Based on the foregoing analysis, the following assumption is advanced:
H5: *Government environmental attention can positively moderate the impact of FinTech on low-carbon development of manufacture industry.*

2.5 FinTech, Human Capital and Low-Carbon Development of Manufacture Industry

Human capital, embodying the knowledge, skills, and capabilities of the labor force, serves as a core enabler, accelerating the manufacturing sector's transition to low-carbon development through green technology innovation (Tian *et al*., 2025). It serves not only as a core driver of technological innovation but also as a critical enabler for the widespread adoption of green technologies and the achievement of sustainable development goals in manufacturing (Lin *et al*., 2023).

For the manufacturing sector, high-quality human capital functions as a developmental engine, playing an irreplaceable role in fostering technological innovation and advancing the application of green technologies. Under the current economic landscape, the manufacture industry urgently requires reductions in energy consumption and carbon emissions to achieve green transformation (Jiang *et al.*, 2023). Talents equipped with professional expertise and skills can provide sustained impetus for the sector's development through their professional competence and innovative capabilities (Chang *et al*., 2024). Not only can they develop more efficient and environmentally friendly production technologies, but they also actively promote the widespread adoption of green technologies in corporate production, thereby elevating the green development standards of the manufacture industry (Sakilu and Chen, 2025).

Scholarly work has documented, from diverse perspectives, the positive influence of human capital in advancing environmental governance. Zafar *et al*., (2019) utilized empirical methodologies to reveal that human capital investment significantly accelerates the integration of energy-efficient innovations across residential, mobility, and production domains, consequently fostering ecological enhancement. Obobisa (2024) uncovered a robust positive association between human capital accumulation and carbon mitigation performance, emphasizing that highly educated individuals demonstrate stronger propensity to actively adhere to environmental regulations and adopt sustainable practices， thereby offering a micro-behavioral rationale for the environmental efficacy of human capital investments. Notably, research by Xu *et al*.,

(2025) into firm heterogeneity found that human capital density exerts differential impacts on carbon intensity, with notably stronger effects observed in private ownership, light industry, and non-provincial capital contexts，a pattern consistent with human capital's contribution to optimizing production and management pathways. This suggests that human capital may operate through channels such as optimizing production technology pathways and enhancing management efficiency. Collectively, these studies indicate that strengthening human capital accumulation provides critical support for digitally driven sustainable production transformations. Based on the foregoing analysis, the following assumption is advanced:
H6: *Human capital promotes low-carbon development of manufacture industry.*

According to the above analysis, FinTech can assist manufacturing enterprises in introducing advanced low-carbon technologies (Zhou *et al*., 2025; Wang *et al*., 2025), by providing financial support (Yan *et al*., 2022; Li *et al*., 2024a), and reducing information asymmetry (Hasan *et al*., 2024). Meanwhile, talents equipped with professional knowledge and skills can accelerate the application and dissemination of these technologies, driving enterprises toward low-carbon production. This notion is also supported by numerous scholars. Chondrogianni and Tsalaporta (2023), utilizing data from 14 developing countries, found that human capital reduces carbon emissions by promoting green technology innovation. Furthermore, Umar *et al*., (2022) indicated that human capital achieves emission reductions by facilitating energy structure transitions and enhancing environmental awareness. Khachaturyan (2022) emphasized the necessity of strengthening workforce capacity-building to meet the demands of digital economic development, highlighting the critical role of intellectual and digital skills in sustaining economic growth under low-carbon contexts. Taken together, these studies reveal that human capital acts as an essential pipeline for the flow of green technologies, while also serving as a pivotal factor that mediates how FinTech influences low-carbon development in the manufacturing sector. Based on the foregoing analysis, the following assumption is advanced:
H7: *Human capital can positively moderate the impact of FinTech on low-carbon development of manufacture industry.*

The specific framework of influence mechanisms in this study is illustrated in Figure 1, where the dashed arrows indicate potential moderating effects.

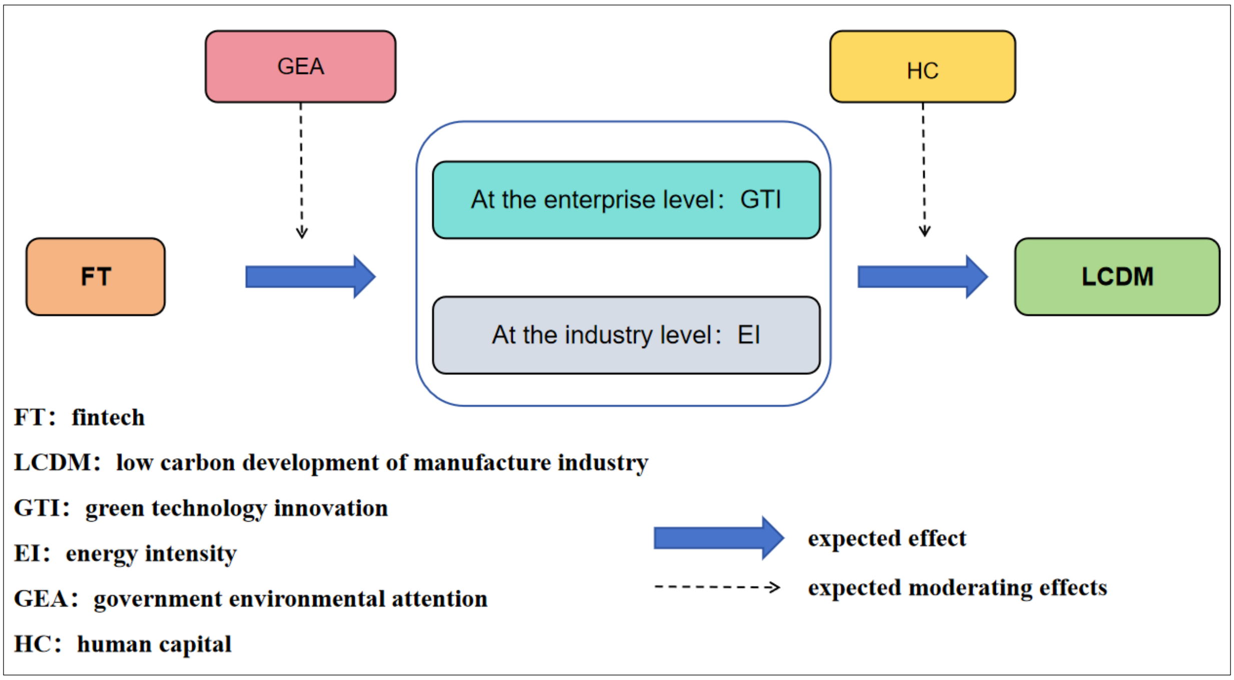

Figure 1: Impact mechanism framework

3. MODELS, VARIABLES AND DATA

3.1 Econometric Model

Guided by prior research (Jiang, 2022; Wu *et al*., 2025), this study leverages a two-way fixed effects within a two-step procedure framework to assess FinTech's impact on manufacturing decarbonization via mediators (green technology innovation and energy intensity), while also evaluating the moderating effects of government environmental attention and human capital.

First, to test H1, H2, H3, H4, and H6, the following baseline model is constructed:

$$LCDM_{it} = \alpha_0 + \alpha_1 FT_{it} + \alpha_2 Control_{it} + \delta_i + \sigma_t + \varepsilon_{it} \quad (1)$$

$$GTI_{it} = \eta_0 + \eta_1 FT_{it} + \eta_2 Control_{it} + \delta_i + \sigma_t + \varepsilon_{it} \quad (2)$$

$$EI_{it} = \lambda_0 + \lambda_1 FT_{it} + \lambda_2 Control_{it} + \delta_i + \sigma_t + \varepsilon_{it} \quad (3)$$

$$GTI_{it} = \beta_0 + \beta_1 GEA_{it} + \beta_2 Control_{it} + \delta_i + \sigma_t + \varepsilon_{it} \quad (4)$$
$$LCDM_{it} = \gamma_0 + \gamma_1 HC_{it} + \gamma_2 Control_{it} + \delta_i + \sigma_t + \varepsilon_{it} \quad (5)$$

Where $LCDM_{it}$ represents the low-carbon development level of the manufacture industry in region at time , FT_{it} denotes its FinTech level, GTI_{it} indicates its green technology innovation level, EI_{it} represents its energy intensity, GEA_{it} reflects its government environmental attention, and HC_{it} measures its human capital level. $Control_{it}$ represents the following control variables: population density (PD), foreign direct investment (FDI), openness to the outside world (OP), artificial intelligence (AI), and resident income (RI). denotes individual fixed effects, represents time fixed effects, and is the error term.

Similarly, to verify H3, H5 and H7, the following models are constructed:

$$GTI_{it} = \mu_0 + \mu_1 FT_{it} + \mu_2 GEA_{it} + \mu_3 FT_{it} * GEA_{it} + \mu_4 Control_{it} + \delta_i + \sigma_t + \varepsilon_{it} \quad (6)$$
$$LCDM_{it} = \nu_0 + \nu_1 GTI_{it} + \nu_2 HC_{it} + \nu_3 GTI_{it} * HC_{it} + \nu_4 Control_{it} + \delta_i + \sigma_t + \varepsilon_{it} \quad (7)$$

Here, the sign of interaction term coefficient μ_3, ν_3 respectively indicating the direction of the moderating effects of government environmental attention and human capital in the process of FinTech influencing the low-carbon development of the manufacture industry.

3.2 Variable Interpretation

3.2.1 Explained Variable

Low-carbon development in manufacturing (LCDM). Referring to Guo and Fu (2023), carbon emission efficiency is employed as the metric to quantify the level of low-carbon development. Additionally, based on Guo *et al*., (2025), the DEA-SBM model is utilized to comprehensively evaluate the low-carbon development level in manufacturing. The selected indicators are detailed in Table 1.

Table 1: Decision Unit Indicators

Dimension	Indicator	Measurement method
Investment factor	Capital investment	Funds for developing new products in industrial enterprises above designated size
	Resource input	Total energy consumption converted to standard coal
	Labor input	Number of R&D personnel in industrial enterprises above designated size
Expected output	Economic output	Industrial output
	Industrial innovation output	Sales revenue from new products of industrial enterprises above designated size
		Number of effective invention patents for industrial enterprises above designated size
Unexpected output	Carbon emission	Carbon emissions from manufacturing industry

Source: Self statistics

3.2.2 Core Explanatory Variables

FinTech (FT). Following the methodology of Li *et al*., (2020), a regional financial development level indicator is constructed by using the advanced search feature of Baidu News with “FinTech” as the keyword.

3.2.3 Mediating Variables

Green Technology Innovation (GTI). Following Sun and Li (2024), it is measured by the natural logarithm of the number of green invention patent applications in each province.

Energy Intensity (EI). With reference to Li and Guo (2025), it is measured by taking the natural logarithm of the total energy consumption.

3.2.4 Adjusting Variables

Government Environmental Attention (GEA). Following Wang *et al.*, (2022), an environmental keyword lexicon is constructed. The proportion derived from matching this lexicon with government work reports is multiplied by 100 to serve as the indicator for local government environmental attention.

Human Capital (HC). With reference to Lei *et al*., (2025), it is measured by the ratio of the number of students enrolled in regular institutions of higher education to the year-end total population of the region.

3.2.5 Control Variables

Population Density (PD). Following Sogut *et al*., (2025), it is measured by the ratio of the year-end resident population to the land area.

Foreign Direct Investment (FDI). With reference to Guo *et al*., (2025), actual FDI data from 2004 to 2023 is selected and converted into Renminbi (RMB) based on the annual average USD exchange rate.

Openness (OP). Following Zhang *et al*., (2025b), it is measured by the ratio of foreign direct investment to GDP. Artificial Intelligence (AI). With reference to Yang *et al*., (2023), it is measured by the logarithm of the number of artificial intelligence enterprises in each province.

Resident Income (RI). Following Zhou *et al*., (2025), it is measured by the logarithm of per capita disposable income. Degree of industrialization (DI). With reference to Cui (2022), it is measured by the ratio of industrial added value to regional GDP.

3.3 Data Sources

In light of data availability constraints, this study employs panel data from 30 mainland Chinese provinces (omitting Tibet Autonomous Region, Hong Kong, Macao, and Taiwan) spanning the period 2004-2023 to construct the analytical sample for empirical investigation. Data are sourced from the China Statistical Yearbook, China Energy Statistical Yearbook, provincial statistical yearbooks, the National Bureau of Statistics, Baidu News, government work reports, the CEDC database, and the CEADs-China carbon accounting database.

Prior to conducting the empirical analysis, unit root tests and collinearity tests were performed on the variables to ensure data stability. The results, shown in Table 2, indicate that all variables are stationary after first-differencing and have VIF values below 10. Thus, all variables are stable and free from severe multicollinearity issues. The variables, along with their operational definitions and data origins, are systematically summarized in Table 3. Meanwhile, Table 4 delivers the descriptive statistics for the entire set of variables under investigation.

Table 2: Variance inflation factor

Variables	VIF	1/VIF
AI	9.97	0.100311
FT	7.04	0.141982
GTI	6.95	0.143975
GEA	1.18	0.846995
EI	4.30	0.232394
PD	3.06	0.327029
HC	2.01	0.496747
FDI	1.59	0.629591
OP	1.13	0.881252
Mean VIF	4.14	

Source: Authors' calculation

Table 3: Variable definition and data source

Variables	Symbol	Measure	Date sources
Low carbon development of manufacturing industry	LCDM	Indicator to measure the carbon emission efficiency of manufacturing industry	Calculating using SBM super efficiency model
FinTech	FT	Financial Development Level Indicator	Baidu News
Green technology innovation	GTI	The natural logarithm of the number of green invention patent applications	CNRDS
Energy intensity	EI	Logarithmic total energy consumption	China Statistical Yearbook
Government environmental attention	GEA	Building an Environmental Attention Lexicon	Ministry of Finance of the People's Republic of China
Human capital	HC	The ratio of the number of students enrolled in regular higher education institutions to the total population of the region at the end of the year	China Statistical Yearbook
Population density	PD	Year-end resident population to land area ratio	China Statistical Yearbook
Foreign direct investment	FDI	Actual foreign direct investment flow data by province	China Trade and Economic Statistics Yearbook
Openness	OP	The ratio of foreign direct investment to GDP	China Trade and Economic Statistics Yearbook

Variables	Symbol	Measure	Date sources
Artificial intelligence	AI	The logarithmic value of the number of artificial intelligence enterprises in each province	Mark database
Resident income	RI	Per capita disposable income	China Statistical Yearbook
Degree of industrialization	DI	The ratio of industrial added value to regional gross domestic product	China Statistical Yearbook

Source: Authors' calculation

Table 4: Variables descriptive statistics

Variables	Observations	Mean	Std. Dev	Minimum	Maximum
LCDM	600	0.80	0.31	0.09	1.38
FT	600	4.91	2.12	0.00	9.39
GTI	600	6.52	1.77	0.00	10.14
EI	600	2.04	0.08	1.81	2.28
GEA	600	4.90	0.23	4.04	5.58
HC	600	1.92	0.70	0.46	4.37
PD	600	5.44	1.28	2.01	8.28
FDI	600	2.22	2.04	0.01	12.10
OP	600	0.54	1.12	0.01	10.50
AI	600	7.28	1.81	3.53	12.18
RI	600	1.22	0.93	0.03	5.06

Source: Authors' calculation

4. EMPIRICAL ANALYSIS

4.1 Benchmark Effect Regression

To test H1, H2, and H3, this study employs a two-way panel fixed-effects model, estimated using Driscoll and Kraay (D-K) standard errors. Table 5 displays the results.

Table 5: Benchmark effect regression results

Variables	（1）	（2）	（3）
	GTI	**EI**	**LCDM**
FT	0.1085*** (0.0369)	-0.0089*** (0.0029)	0.0528* (0 .0275)
PD	1.1713*** (0.3039)	0.0665*** (0.0237)	0 .0147 (0.2265)
FDI	0.0445*** (0.0101)	-0.0048*** (0.0008)	0.0196*** (0.0075)
OP	-0.0747*** (0.0225)	-0.0002 (0.0018)	0.0030 (0.0168)
AI	0.1795** (0.0703)	-0.0116** (0.0055)	-0.1974*** (0.0524)
RI	-0.3251*** (0.0275)	-0.0388*** （0.0057）	-0.1171** (0.0541)
_cons	-1.3534* (1.5782)	1.8614*** （0.1233）	1.993* (1.1761)
Year-fixed effect	√	√	√
Country-fixed effect	√	√	√
N	600	600	600
R-square	0.9770	0.9297	0.5752

*p＜0.1；**p＜0.05；***p＜0.01.The standard error in parentheses

Prior theoretical analysis suggests that the development of FinTech may promote low-carbon development in manufacture by facilitating green technology innovation and reducing energy intensity. This section will delve into these two potential pathways.

Model (3) in Table 5 shows a coefficient of 0.0528 for FinTech, significant at the 10% level, supporting the proposition that it facilitates low-carbon development in China's manufacturing industry. Specifically, when all other conditions remain unchanged, for every one-unit increase in FinTech, the level of low-carbon development in the manufacture industry rises by 0.0528 units. This result is in line with the findings of Li *et al*., (2024b). Hence, H1 is validated.

Li *et al*., (2024), through an analysis of data from listed companies, discovered that FinTech can incentivize firms' green technology innovation by alleviating their financing constraints. Moreover, model (1) reports a coefficient of 0.1085 for FinTech, significant at the 1% level, demonstrating its positive effect on green technology innovation. Our result corroborates the earlier evidence presented by Ferri *et al*., (2025). In addition, a substantial body of research provides evidence for the assertions that green technology innovation can reduce carbon emissions in the manufacture industry (Shan and Shao, 2024; Xu *et al.,* 2021), enhance energy efficiency (Lee *et al.,* 2024; Wurlod and Noailly, 2018), and accelerate the development of renewable energy (Shan *et al.,* 2021). It indicates that the pervasive nature of digital technology serves as a catalyst for cross-disciplinary integration between green technologies and those from diverse fields, thereby elevating the quality of firms' existing green innovation outputs and helping curb corporate carbon emissions (Barbieri *et al*., 2023). Given this theoretical connection, it can be argued that the enhanced effect of FinTech-driven green technology innovation acts as a fundamental driver in the low-carbon development of manufacture industry. Therefore, H2 is validated.

Wu *et al*., (2025), through an analysis of data from 278 prefecture-level cities in China, found that FinTech can reduce energy intensity by enhancing capital allocation efficiency. Moreover, as shown in Model (2), the coefficient of FinTech is -0.0089 at the 1% significance level, indicating that FinTech can lower energy intensity. This finding is also consistent with the research results of Li and Yue (2024).In addition, a substantial body of research provides evidence for the claims that reducing energy intensity can decrease carbon emissions in the manufacture industry (Feng *et al*., 2023b; Pan *et al*., 2022), improve resource utilization efficiency (Liu *et al*., 2025a; Zhao *et al.,* 2025), and incentivize the development of energy-saving technologies (Feng *et al*., 2023a; Li *et al*., 2025a). It suggests that the need for firms to reduce energy intensity can drive them to optimize production processes, arrange equipment operation times reasonably, and adopt energy-saving production techniques, all of which are beneficial for enhancing firms' energy utilization efficiency. Given this theoretical connection, it can be argued that the enhanced effect of FinTech-driven reduction in energy intensity acts as a crucial pathway in the low-carbon development of manufacture industry. Therefore, H3 is validated.

4.2 Heterogeneity Analysis

Given the regional disparities in economic development and financial growth across China, the impact of FinTech on the low-carbon development of the manufacturing sector is likely to exhibit regional heterogeneity (Lee *et al*., 2025). To further investigate the effect of heterogeneity in FinTech development levels, and following the approach of Li and Guo (2025), the sample is divided into a high FinTech development level group (top 15) and a low-level group (bottom 15) based on the ranking of provinces by their average FinTech development level from 2004 to 2023. Group-wise regressions are then conducted. Table 6 displays the results.

Table 6: Heterogeneity analysis

Explained variable: LCDM		
Variable	**High**	**Low**
FT	0.0832** (0.0323)	0.0225 (0.0481)
Controls	Yes	Yes
Year-fixed effect	√	√
Country-fixed effect	√	√

$*p<0.1$；$**p<0.05$；$***p<0.01$. The standard error in parentheses

The results from the table indicate that the promoting effect of FinTech on low-carbon development of manufacture industry is only significant in cities with higher levels of financial development. This observed pattern can be attributed to the following potential reasons:

Firstly, regions with a high FinTech development level facilitate technology commercialization through well-established venture capital and green financial products (Wu *et al*., 2025), whereas regions with a low-level are constrained by a monolithic financial market structure, making it difficult to form effective investment channels.

Secondly, manufacturing firms in low level regions often exhibit insufficient digitalization levels, lack managerial standardization, and have low acceptance of emerging financing models (Gao and Liang, 2025). These limitations make it difficult for them to meet the risk management and compatibility requirements of FinTech, consequently hindering the effective reach and penetration of its enabling effects.

Thirdly, the full realization of FinTech's efficacy hinges on the collective support of digital infrastructure, interdisciplinary talent, and forward-looking policies (Zhang *et al*., 2025a). Regions with a high FinTech development level possess significant advantages in this regard, while low levels regions face constrained development potential due to insufficient foundational elements.

4.3 Analysis of Regulatory Effects

The preceding analysis has examined the mechanisms through which FinTech directly fosters low-carbon development in the manufacture industry, as well as indirectly facilitates it by promoting green technology innovation and reducing energy intensity. This section focuses on analyzing the moderating effects of government environmental attention and human capital on these indirect effects, Table 7 displays the results.

Table 7: Regression results of moderation effect

Variables	（4）	（5）
	GTI	**LCDM**
GEA	0.1129* (0.6737)	
FTGEA	0.0816*** (0.0305)	
GTI		1.1568*** (0.0311)
HC		0.0894* (0.0463)
GTIHC		0.1120*** (0.0337)
Controls	Yes	Yes
Year-fixed effect	√	√
Country-fixed effect	√	√

*p＜0.1；**p＜0.05；***p＜0.01. The standard error in parentheses

As shown in the results in Column (2), the coefficient for government environmental attention is 0.1129 and significant at the 10% level, indicating that government environmental attention promotes green technology innovation. The coefficient for the interaction term between FinTech and government environmental attention is 0.0816 and significant at the 1% level, suggesting that government environmental attention exerts a significant positive moderating effect. This effect is on the process where FinTech promotes low-carbon development in manufacturing via green technology innovation. Similar conclusions have been drawn by Yuan *et al.*, (2025a) and Liao (2025). Therefore, H4 and H5 are supported.

As shown in the results in Column (3), the coefficient for green technology innovation is 1.1568 and significant at the 1% level, and the coefficient for human capital is 0.0894 and significant at the 10% level. This indicates that both green technology innovation and human capital can promote low-carbon development in the manufacture industry, which is consistent with the findings of Dai *et al*., (2024) and Obobisa (2024). The coefficient for the interaction term between green technology innovation and human capital is 0.1120 and significant at the 1% level, suggesting that human capital exerts a significant positive moderating effect on the process through which FinTech promotes low-carbon development in manufacturing via green technology innovation. This finding aligns with the research results of Liao *et al*., (2024). Therefore, H6 and H7 are validated.

4.4 Robustness test

4.4.1 Endogenous Test (Lagged By One Period)

To mitigate potential estimation bias caused by bidirectional causality among core variables, this paper draws on the research of Li and Guo (2025) and introduces lagged variables to construct a dynamic panel model. Table 8 displays the results. The core variables' coefficients maintain their direction and statistical significance, affirming the robustness of the benchmark regression findings.

Table 8: Test of endogeneity

Variables	（1）	（2）	（3）
	GTI	**EI**	**LCDM**
L.FT	0.1095** (0.0485)	-0.0083*** (0.0021)	0.0448* (0.0263)
L.GEA	0.1231* (0.0654)		
L.HC			0.0898* (0.0530)
L.FTGEA	0.1045*** (0.0357)		
L.GTIHC			0.0403*** (0.0131)
Controls	Yes	Yes	Yes
Year-fixed effect	√	√	√
Country-fixed effect	√	√	√

*p＜0.1；**p＜0.05；***p＜0.01. The standard error in parentheses

4.4.2 Eliminate Extreme Values

To reduce potential interference from outliers on parameter estimation, this paper follows the practice of Guo *et al*., (2025) by conducting winsorization on the core explanatory variable "FinTech" at the 1%, 5%, and 10% quantile levels, respectively. On this basis, the two-way fixed effects model is re-estimated. As shown in Table 9, the persistence of coefficient signs and significance levels for core variables across winsorization thresholds validates the robustness of our initial findings.

Table 9: Threshold effect regression results of excluding extreme values

Variables		**28**			**26**			**24**	
	GTI	**EI**	**LCDM**	**GTI**	**EI**	**LCDM**	**GTI**	**EI**	**LCDM**
FT	0.0942* (0.0514)	- 0.0070*** (0.0024)	0.1376*** (0.0216)	0.0875* (0.0522)	- 0.00818*** (0.0023)	0.1338*** (0.0222)	0.1197** (0.0474)	- 0.0082*** (0.0024)	0.1437*** (0.0226)
GEA	0.1383** (0.0685)			0.1789** (0.07250			0.1264* (0.0713)		
FTGEA	0.0724** (0.0327)			0.0620* (0.0350)			0.0786** (0.0361)		
GTI			0.1460*** (0.0313)			0.1639*** (0.0322)			0.1594*** (0.0353)
HC			0.1029** (0.0483)			0.0972* (0.0524)			0.0985* (0.0540)
GTIHC			0.0368*** (0.0124)			0.0324** (0.0127)			0.0278** (0.0141)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed effect	√	√	√	√	√	√	√	√	√
Country-fixed effect	√	√	√	√	√	√	√	√	√

4.4.3 Increase Control Variables

To address the potential confounding effects of regional industrial composition, we follow the methodology of Gao *et al*., (2025), incorporated "Degree of industrialization" as a control variable into the benchmark model to verify the robustness of the aforementioned results. Table 10-11 display the results, after including this control, the signs and statistical significance of the key estimated coefficients remained stable, affirming the robustness of our findings.

Table 10: Robustness testing of benchmark regression analysis (Increase control variables)

Variables	（6）	（7）	（8）
	GTI	**EI**	**LCDM**
FT	0.0656* (0.0357)	-0.0076*** (0.0029)	0.0494* (0.0279)
PD	0.8919*** (0.2928)	0.0751*** (0.0238)	-0.0075 (0.2285)
FDI	0.0378***	-0.0046***	0.0191**

Variables	（6）	（7）	（8）
	GTI	**EI**	**LCDM**
	(0.0096)	(0.0008)	(0.0075)
OP	-0.0392* (0.0220)	-0.0013 (0.0018)	0.0058 (0.1721)
AI	0.1517** (0.0673)	-0.0107* (0.0055)	-0.1996*** (0.0525)
RI	-0.2128*** (0.0709)	-0.0422*** (0.0058)	-0.1082* (0.0554)
DI	0.0003*** (0.0000)	-0.0001*** (0.0000)	-0.0001 (0.0000)
_cons	-0.1286 (1.5169)	1.8236*** (0.1233)	2.0905* (1.1838)
Year-fixed effect	√	√	√
Country-fixed effect	√	√	√

*p＜0.1；**p＜0.05；***p＜0.01.The standard error in parentheses

Table 11: Robustness test of moderation effect (Increase control variables)

Variables	（4）	（5）
	GTI	**LCDM**
FTGEA	0.0694** (0.0293)	
GTIHC		0.0417*** (0.0128)
Controls	Yes	Yes
Year-fixed effect	√	√
Country-fixed effect	√	√

*p＜0.1；**p＜0.05；***p＜0.01. The standard error in parentheses

5. CONCLUSION AND DISCUSSION

5.1 Conclusion

Based on panel data from 30 Chinese provinces spanning 2004 to 2023, this study examines the impact of FinTech, green technology innovation, and energy intensity on the low-carbon development of the manufacture industry, as well as the moderating roles of government environmental attention and human capital in these processes. The main conclusions are as follows:

Firstly, FinTech has a direct promoting effect on the low-carbon development of manufacture industry, but this effect is only significant in regions with high levels of FinTech development. Secondly, from the perspective of mediating effects, FinTech can indirectly promote the low-carbon development of the manufacture industry through green technology innovation and reducing energy intensity. Finally, in terms of moderating effects, government environmental attention primarily strengthens the driving role of FinTech in green technology innovation (research and development stage), while human capital significantly enhances the transformation efficiency of green technology innovation for low-carbon development (achievement transformation stage).

5.2 Discussion

The empirical findings of this study reveal the complex mechanisms through which FinTech influences the low-carbon development of the manufacturing sector. These findings not only validate theoretical expectations but also stimulate deeper reflection on existing theories.

5.2.1 From the Perspective of Main Effect

The study confirms that FinTech promotes the low-carbon development of the manufacture industry, but this effect is only significant in regions with high levels of FinTech development. This finding corroborates the digital divide theory (Jiang and Luo, 2024). It indicates that FinTech is not a universally inclusive solution; its effectiveness is constrained by regional financial conditions, and the outcomes of its technological applications are jointly influenced by the institutional environment and social resources.

5.2.2 From the Perspective of Mediating Effect

The study confirms that FinTech can promote the low-carbon development of the manufacture industry by stimulating green technology innovation (supply-side driven) and reducing energy intensity (demand-side driven). This evidence offers valuable insights for the development of differentiated carbon mitigation policies targeted at China's manufacture industry: Given the significant disparity in technological levels among enterprises within the industry, FinTech can not only support innovation in high-tech enterprises (Yalcin *et al.*, 2025), but also assist traditional enterprises in energy-saving renovations (Umar *et al*., 2025).

5.2.3 From the Perspective of Moderating Effect

It is particularly worthy of in-depth exploration to examine the stage-specific moderating effects of government environmental attention and human capital. This finding reveals the temporal division of labor between "institution-driven" and "talent-driven" forces in the process of green transformation of the manufacture industry: institutional leadership provides innovation impetus in the initial stage of transformation, while high-quality talents constitute a sustained driving force during the deepening stage (Li *et al*., 2024). This stage-based moderating model offers a new theoretical perspective for understanding the differences in the driving forces of low-carbon transformation across regions at different development stages.

6. Inspiration

6.1 Theoretical Contribution

The main theoretical contributions of this study are as follows:

First of all, this study analyzes the impact of FinTech on the low-carbon development of the manufacture industry from an industry perspective and deepens the current theoretical understanding of the driving factors for the low-carbon development of the manufacture industry through research on micro-mechanisms.

Secondly, this study elucidates the mechanism through which FinTech promotes the low-carbon development of the manufacture industry by driving technological progress and enhancing efficiency, by analyzing the mediating roles of green technology innovation and energy intensity. This enhances its theoretical significance in the field of sustainable development research.

Finally, based on China's specific development context, this study uncovers the synergistic mechanism among FinTech, government policies, and human resources, thereby expanding the theoretical framework of green growth in the context of transitional economies.

6.2 Practical Insights

6.2.1 From the Main Effect Results

The heterogeneity results indicate that regional financial foundations determine the effectiveness of FinTech in promoting the low-carbon development of the manufacture industry. Therefore, regions with weak financial foundations need to enhance the integration of FinTech with traditional financial services, and strengthen financing support for the low-carbon development of the manufacture industry by innovating green credit products and optimizing service processes. Meanwhile, manufacturing enterprises should proactively introduce FinTech tools to accelerate their green transformation by improving the efficiency of capital management and resource allocation.

6.2.2 From the Mediating Effects Results

The government should establish a risk fund for green technology innovation, with a focus on supporting projects during the research, development, and experimental phases to address the financing challenges faced by early-stage enterprises. Financial institutions, in collaboration with enterprises, should launch a combined service package of "energy-efficiency loans + digital energy management systems". By utilizing the Internet of Things to monitor energy consumption and linking energy-saving performance to financing terms, a sustainable incentive mechanism for energy conservation and emission reduction can be established.

6.2.3 From the Moderating Effects Results

Building on the moderating effects of government environmental attention and human capital at different stages, this study proposes constructing a phased, multi-stakeholder collaborative policy system: At the initial technology R&D stage, the government should strengthen policy guidance by incorporating green technology innovation performance into local evaluation metrics, while reducing innovation barriers through R&D subsidies and public platform development. At the subsequent achievement transformation stage, focus should be placed on cultivating interdisciplinary talent, promoting cross-disciplinary programs in universities, and supporting university-enterprise partnerships in establishing practical training bases. Ultimately, through coordination among government, industry, academia, research institutions, and financial organizations, a full-chain support system from technology development to industrialization should be established to ensure effective translation of innovation outcomes into productive forces.

7. Limitations and Future Research

Firstly, while this study offers preliminary insights through heterogeneity analysis, future research should explore development pathways tailored to China's diverse regions across multiple dimensions. For instance, comparing disparities between eastern, central, and western regions, or between coastal and inland areas, could yield more targeted regional policy recommendations.

Secondly, although the moderating roles of government environmental attention and human capital were examined, this study does not cover all critical contextual factors. Future research could incorporate more diverse contextual elements, such as public environmental supervision or external knowledge spillovers, and further delve into the potential interactive effects among existing moderating variables, such as government attention and human capital.

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