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Impact of Digitalization on Low-Carbon Transition in Manufacturing

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Abstract: *Against the backdrop of global climate change, manufacturing, as a major source of carbon emissions, plays a critical role in achieving the "dual-carbon" goals. The rapid development of digital technologies provides new opportunities for low-carbon transition in manufacturing. This study utilizes panel data from 30 Chinese provinces from 2011 to 2022 to construct a relational model among digitalization, low-carbon transition in manufacturing, and technological innovation, tested using Stata 18.0. The results highlight the significant mediating role of technological innovation in promoting the impact of digitalization on low-carbon transition in manufacturing.*

Keywords: *Digital Economy Development Level; Manufacturing; Low-Carbon Transition; Technological Innovation*

1. Introduction

Under the intertwined context of accelerating global climate governance and the digital technology revolution, the low-carbon transition of manufacturing faces dual historical missions: achieving the "dual-carbon" goals and advancing digital civilization. While digital technologies offer new pathways for manufacturing transformation, many enterprises struggle to convert digital tools into tangible emission reductions due to insufficient technological innovation capabilities. Existing research inadequately explains how digitalization drives low-carbon transition, often oversimplifying technological pathways or neglecting regional disparities in digital infrastructure. This study constructs a dynamic analytical model using provincial data from China to systematically trace the pathways through which digitalization facilitates emission reduction via technological innovation. The findings aim to bridge regional transition gaps, optimize policy design, and foster synergistic development of digitalization and low-carbon initiatives.

2. Literature Review

2.1 Mechanisms of Digitalization on Low-Carbon Transition in Manufacturing

Digital transformation significantly enhances corporate carbon performance by promoting green technological innovation (Fang Jianguo et al., 2025)[1]. From a structural reform perspective, the digital economy facilitates inter-regional collaborative transition through spatial spillover effects, driven by green innovation, resource allocation efficiency, and green credit support (Chen Fuzhong et al., 2024)[2]. Heterogeneity analysis reveals stronger carbon reduction effects of digitalization in eastern regions and technology-intensive industries (Hu Yumeng et al., 2023)[3]. At the firm level, digital finance reduces carbon emissions by enabling digital transformation, though the mediating role of technological application remains weak, with non-state-owned enterprises showing more responsiveness (Long Chi et al., 2023)[4].

2.2 Mechanisms of Digitalization on Technological Innovation

Digitalization drives green innovation by optimizing resource allocation, increasing R&D investment,and attracting high-end talent (Liu Zhiming et al., 2024)[5]. Strategically, digitalization enhances information transparency and market anticipation, indirectly fostering low-carbon innovation, with higher efficiency in private enterprises (Yin Ximing et al., 2023)[6]. Regional heterogeneity shows that eastern regions leverage digital infrastructure for technological spillovers, while central and western

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regions rely on digital breakthroughs (Xu Xing et al., 2023)[7]. Synergies among technology, resources, and institutions are critical for low-carbon transition.

2.3 Mediating Role of Technological Innovation

In advanced manufacturing, technological innovation capability serves as the core driver and key for enterprises to achieve high-quality development (Bai Wanting et al., 2024)[8].On one hand, technological innovation propels the optimization of resource allocation, enhances production efficiency, optimizes input scale and management practices, thereby elevating the overall technological innovation capability of enterprises (Tian Xiaoxiao et al., 2023)[9]. This facilitates the comprehensive upgrading and transformation of the manufacturing sector.On the other hand, technology constitutes the core competitiveness of enterprises and acts as the intrinsic driving force for manufacturing development (Zhang Shaofeng et al., 2023)[10]. The application of digital technologies such as big data and artificial intelligence streamlines technological innovation. This enables manufacturing enterprises to increase the number of patent applications and the probability of patent grants, laying a solid foundation for technological innovation R&D (Lin Kongtuan et al., 2024)[11].

3. Theoretical Analysis

3.1 The Impact of Digitalization on Low-Carbon Transition in Manufacturing

1) From the perspective of technological penetration. Digitalization deeply integrates into the entire production process of manufacturing, driving intelligent transformation of production processes. Intelligent sensors and IoT technologies optimize equipment energy consumption in real time, machine learning algorithms predict and reduce redundant production, systematically compressing energy consumption and emission intensity in high-carbon segments. 2) From the perspective of industrial ecosystem reconstruction. Data elements drive resource aggregation towards high-value-added segments such as design, R&D, and recycling, forcing the exit of high-carbon production capacity and reconstructing a low-carbon industrial ecosystem. 3) From the perspective of governance model innovation. Digitalization establishes a closed-loop management system for carbon emissions ("monitoring-accounting-trading"). Blockchain technology secures carbon data, artificial intelligence dynamically matches carbon quotas with emission reduction demands, activating market incentives and realizing a paradigm shift in environmental regulation from administrative control to market-driven mechanisms.

3.2 The Impact of Digitalization on Technological Innovation

1) From the perspective of technological empowerment. Digitalization reconstructs technology R&D paradigms, reducing innovation trial-and-error costs. Real-time data flows accurately identify technological needs and market gaps, driving R&D resources to concentrate on high-value areas, accelerating technology iteration and commercialization. 2) From the perspective of collaborative innovation. Digital platforms integrate resources across upstream and downstream industrial chains, promoting cross-organizational knowledge sharing and collaborative development. Cloud-based collaboration tools modularize and parallelize R&D processes, shortening technology commercialization cycles. 3) From the perspective of dynamic responsiveness. Digital systems capture technology trends and user demands in real time, rapidly adapting to market changes, building sustainable technological competitive advantages, and enhancing enterprise agile innovation capabilities.

3.3 The Impact of Technological Innovation on Low-Carbon Transition in Manufacturing

1) From the perspective of energy efficiency. Green technological innovation reduces pollutant emissions and energy consumption, lowering corporate environmental costs and improving energy efficiency. 2) From the perspective of industrial structure. Technological innovation drives manufacturing towards high-end, intelligent, and green development, promoting industrial structure optimization and upgrading; low-carbon technological innovation and industrial structure upgrading mutually reinforce each other, reallocating resources from high-carbon, low-value-added segments to low-carbon, high-value-added segments. 3) From the perspective of environmental regulation. The inducement effect of technological progress and the spillover effect of technological innovation drive the formulation and enforcement of environmental regulations, facilitating low-carbon transition in

manufacturing.

Based on the above relationships, this study constructs the following theoretical model (Figure 1):

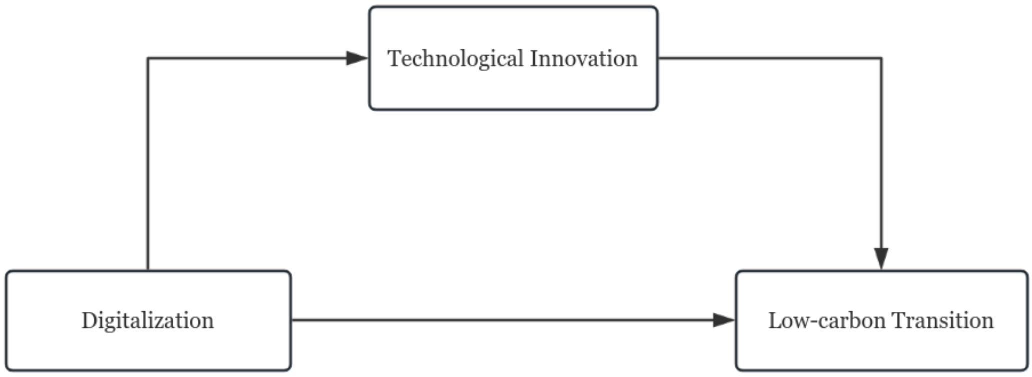

Figure 1 Theoretical Model

$$LCT_{i,t} = \alpha_0 + \alpha_1 DEIQ_{i,f} + \alpha_2 control_{i,t} + \varepsilon_{i,t} \quad (1)$$

$$LCT_{i,t} = \beta_0 + \beta_1 TECH_{i,t} + \beta_{2control_{i,t}} + \varepsilon_{i,t} \quad (2)$$

$$LCT_{i,t} = \gamma_0 + \gamma_1 DEIQ_{i,f} + \gamma_2 TECH_{i,t} + \gamma_3 control_{i,t} + \varepsilon_{i,t} \quad (3)$$

Model (1) validates the impact of the digital economy development level (DEIQ) on low-carbon transition (LCT). Model (2) validates the impact of the mediating variable (TECH) on low-carbon transition (LCT). Model (3) further verifies whether the digital economy development level (DEIQ) still has an impact on low-carbon transition (LCT) after controlling for the mediating variable. Based on the regression logic of mediating effect testing, if the coefficients are significant, Model (2) is used to test the impact of the digital economy development level on the mediating variable. If the coefficients are significant, Model (3) is analyzed: if the coefficient in Model (3) is significantly non-zero and the absolute value of the coefficient in Model (3) is smaller than that in Model (1), it indicates that the digital economy development level affects low-carbon transition through the mediating variable (TECH).

4. Empirical Analysis

4.1 Sample Selection and Data Sources

This paper selects the panel data of 30 provinces in China from 2011 to 2022. After strict screening and eliminating the data of provinces that do not meet specific conditions, 360 valid observation samples are finally retained. To comprehensively assess the development level of the digital economy and obtain data support for the low-carbon transformation of the manufacturing industry, detailed data from the Digital Finance Research Center of Peking University, the China Research Data Service Platform, the "China Industrial Statistical Yearbook", the "China Statistical Yearbook", and the statistical yearbooks of various provinces were obtained. Data on technological innovation and invention patents were also obtained from the "China Science and Technology Statistical Yearbook". The data required for other research variables were uniformly sourced from Mark Data Network, ensuring the comprehensiveness and accuracy of the data.

4.2 Descriptive statistical analysis

In this paper, Stata 18.0 software is used for descriptive statistical analysis of each variable, and the results are shown in Table 1:

Through the descriptive statistical analysis of the sample population in the following table, it is found that the digital economic development level (DEIQ) of each province varies greatly, with an average of 5.34e-09, but the standard deviation is 0.7026, the minimum is -1.0435, and the maximum is 3.3682, which shows that there is a large room for improvement. The average value of low-carbon transformation (LCT) of manufacturing industry is 2. 0103, and the standard deviation is 0. 8868, indicating that the

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degree of low-carbon transformation of manufacturing industry in different provinces is different, and the level of low-carbon transformation in some provinces is low. The average value of technological innovation (TECH) is 2.2564, the standard deviation is 0.1508, the maximum value is 2.5176, and the minimum value is 1.6711It shows that the level of technological innovation in different provinces is quite different.

Table 1 Descriptive Statistical Analysis of Variables

variable name	sample size	average	standard deviation	minimum	maximum
IS	360	1.3537	0.7444	0.53	5.28
Urb	360	0.6012	0.1205	0.35	0.9
DO	360	0.2713	0.2805	0.01	1.46
gov	360	0.2590	0.1115	0.11	0.76
Er	360	1.9089	0.6287	0.9400	3.5849
TECH	360	2.2564	0.1508	1.6711	2.5176
DEIQ	360	5.34e-09	0.7026	-1.0435	3.3682
LCT	360	2.0103	0.8868	0.3893	5.2936

4.3 Correlation analysis

Through correlation analysis, the results are shown in Table 2 below. As can be seen, The coefficients of digital economic development level (DEIQ) and technological innovation (TECH), technological innovation (TECH) and low-carbon transformation of manufacturing industry are 0. 7179, 0.6736 and 0. 6061, respectively, and there is a significant positive correlation at the level of 1%. Therefore, the regression analysis can be continued.

Table 2 Results of correlation analysis of each variable

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1)DEIQ	1.000							
(2)LCT	0.7191***	1.000						
(3)TECH	0.6736***	0.6061***	1.000					
(4)IS	0.6062***	0.4467***	0.1704***	1.000				
(5)Urb	0.7200***	0.8606***	0.5025***	0.5366***	1.000			
(6)DO	0.7047***	0.7393***	0.5076***	0.4678***	0.7636***	1.000		
(7)gov	-0.4464***	-0.4529***	-0.7799***	0.0421	-0.3224***	-0.4180***	1.000	
(8)Er	-0.2949***	-0.0737	-0.2755***	0.1362***	-0.0289	-0.2508***	0.3631***	1.000

***p<0.01,**p<0.05,*p<0.1

4.4 Regression analysis

Stata 18.0 is used to conduct multiple linear regression analysis on 360 samples from 30 provinces in China. The results of regression analysis are shown in the following table:

According to the data in Table 3, the development level of digital economy is significant at the level of 5%, and there is a positive correlation, indicating that among the 30 provinces in China, the higher the development level of digital economy, the higher the level of low-carbon transformation of manufacturing industry, and the model (1) is established. The regression coefficient of technological innovation is 0.6564. Statistically, it reaches the significance level of 5%, indicating that there is a clear positive correlation between the improvement of technological innovation level and the improvement of low-carbon transformation level of manufacturing industry, that is, the improvement of technological innovation level effectively promotes the investment and achievements of low-carbon transformation of manufacturing industry. Model (3) holds. At present, there are still deficiencies in environmental, economic and social governance in China's provinces, while a good level of digital economic development can promote the green development of manufacturing industry, and the positive role of technological innovation can also enhance the performance of low-carbon transformation of manufacturing industry.

According to the data in Table 4, in model (2), the regression coefficient of the development level of digital economy is 0.1091 and at the significance level of 1%, which significantly predicts the tendency of the level of technological innovation. To sum up, by demonstrating the excellent development level of digital economy, provinces can not only provide broad development space for technological innovation, but also improve the digital management of carbon emissions, thus achieving the

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improvement of production efficiency and the reduction of carbon emissions, and ultimately effectively improve the overall level of low-carbon transformation of manufacturing industry.

Table 3 Results of Multiple Linear Regression Analysis (Low-carbon Transformation of Manufacturing Industry)

variable	DEIQ
DEQI	.1506**
	(2.21)
TECH	.6564**
	(2.28)
IS	-0.533
	(-1.20)
Urb	4.5206***
	(14.00)
DO	.4267***
	(3.21)
gov	-.6817**
	(-2.04)
Er	.1143***
	(2.70)
Constant	-2.2737***
	(-3.17)
R-squared	0.7947
observed value	360

***p<.01,**p<.05,*p<.1

Table 4 Estimation Results of Mediating Effects (Technological Innovation)

variable	DEIQ
DEIQ	.1091***
	(9.76)
LCT	.0222**
	(2.28)
IS	-.0276***
	(-3.43)
Urb	-.0217
	(-0.29)
DO	-.0445*
	(-1.80)
gov	-.7561***
	(-16.21)
Er	.0202***
	(2.59)
Constant	2.4315***
	(75.00)
R-squared	0.7602
observed value	360

***p<.01,**p<.05,*p<.1

5. Research Conclusions and Policy Recommendations

The high-quality development of manufacturing is a focal point of China's economic high-quality development. Technological innovation permeates all elements of productivity, traversing the entire manufacturing process, catalyzing new industries, models, and momentum, and empowering manufacturing towards high-end, intelligent, and green development to address challenges posed by the new wave of technological revolution and industrial transformation. This paper specifically discusses the impact of digitalization on low-carbon transition in manufacturing, the impact of digitalization on technological innovation, and the impact of technological innovation on low-carbon transition in manufacturing. Empirical methods are employed to test these impacts and the mediating role of technological innovation. The main conclusions and recommendations are as follows:

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First, digitalization has a significant positive impact on technological innovation. With the development of the digital economy, manufacturing enterprises are required to enhance innovation levels through mechanisms such as reducing innovation costs, optimizing resource allocation, and strengthening innovation capabilities. Governments should increase investment in digital infrastructure, particularly in 5G networks, data centers, and fiscal subsidies, to support enterprise digital transformation.

Second, technological innovation exerts a significant positive influence on low-carbon transition in manufacturing. Technological innovation is a key driver for promoting low-carbon transition in manufacturing. Enterprises can advance green transformation in manufacturing by developing and applying low-carbon technologies, optimizing production processes, improving energy utilization efficiency, and reducing energy waste. Simultaneously, through R&D and application of more efficient energy management systems, energy consumption structures can be improved to achieve carbon emission reduction.

Third, digitalization significantly promotes low-carbon transition in manufacturing. Under the development context of the new era, the growth of the digital economy necessitates accelerated green and low-carbon transition in manufacturing, expediting process upgrades and re-engineering. Concurrently, the deep integration of digitalization and greening in manufacturing should be promoted, fully leveraging the enabling roles of big data and artificial intelligence in enhancing resource utilization efficiency, management effectiveness, and environmental benefits, thereby accelerating the coordinated digital and low-carbon transformation of traditional manufacturing.

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