Economics & Business Management
ISSN Print: 3079-5214
ISSN Online: 3079-5222
https://doi.org/10.63313/EBM.9164

Digital Transformation and Carbon Emission Reduction in Manufacturing Firms: The Dual Roles of Resource Allocation Efficiency and Green Technology Innovation

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How to cite this paper: Zhang, S. (2026). Digital Transformation and Carbon Emission Reduction in Manufacturing Firms: The Dual Roles of Resource Allocation Efficiency and Green Technology Innovation. *Economics & Business Management*, 5(1), 100-105. ISSN Print: 3079-5214; ISSN Online: 3079-5222. https://doi.org/10.63313/EBM.9164
Published: 2026-03-18

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Abstract

Against the backdrop of China's "Digital China" initiative and "dual carbon" goals, this study examines the impact of digital transformation on carbon emission reduction in Chinese A-share listed manufacturing firms from 2011 to 2022. Using a three-way fixed effects model, we find that digital transformation significantly reduces corporate carbon emission intensity, and this result remains robust after endogeneity treatment and a series of robustness checks. The carbon reduction effect is realized through two core mediating paths: improving resource allocation efficiency and promoting green technology innovation. Further analysis shows that carbon disclosure quality positively moderates the above relationship, and the carbon reduction effect of digital transformation is heterogeneous across firm ownership, regional distribution, and pollution attributes. This study provides empirical evidence for the coordinated digital and green transformation of China's manufacturing sector.

Keywords

Digital Transformation; Carbon Emission Reduction; Resource Allocation Efficiency; Green Technology Innovation; Manufacturing Industry

1. Introduction

Against the backdrop of China's "Digital China" initiative and "dual carbon" goals, the manufacturing industry, as the main source of industrial carbon emissions, is critical to the country's low-carbon transition. Digital transformation is widely regarded as a key driver of manufacturing upgrading, but its carbon reduction mechanism and boundary conditions have not been fully tested in existing studies.

This paper takes 2011-2022 A-share listed manufacturing firms as samples to empirically test the carbon reduction effect of digital transformation, its transmission mechanisms, and heterogeneity. This study enriches the research on

digitalization and corporate environmental governance, and provides practical reference for manufacturing low-carbon transformation.

2. Theoretical Analysis and Research Hypotheses

2.1. Digital Transformation and Corporate Carbon Emissions

Digital transformation reshapes manufacturing firms' production, operation and decision-making through digital technologies such as big data and IoT. It can realize real-time monitoring of energy consumption, optimize production processes, break internal information silos, and reduce energy waste from the source. Although early transformation investment may increase short-term energy consumption, the long-term efficiency improvement will eventually present a net carbon reduction effect.

Hypothesis H1: Digital transformation can significantly reduce the carbon emission intensity of manufacturing firms.

2.2. Mediating Mechanisms of Digital Transformation on Carbon Emission Reduction

Digital transformation drives carbon reduction through two core paths. On the one hand, it reduces information asymmetry, optimizes business processes, and improves resource allocation efficiency, thus reducing energy waste and carbon emissions in production and supply chain. On the other hand, it lowers the R&D cost of green innovation, stimulates firms' green technology innovation activities, and achieves fundamental emission reduction through cleaner production processes and low-carbon technologies.

Hypothesis H2: Digital transformation reduces carbon emission intensity by (a) improving resource allocation efficiency and (b) promoting green technology innovation.

2.3. Moderating Effect of Carbon Disclosure Quality

Carbon information disclosure can reduce the information asymmetry of corporate carbon emissions, facilitate the external supervision of stakeholders, and guide enterprises to adhere to green development. According to voluntary disclosure theory and legitimacy theory, high-quality carbon disclosure is not only a key way for enterprises to demonstrate their environmental responsibility and maintain social legitimacy, but also can enhance external trust and support for enterprises. For manufacturing firms facing strict environmental supervision, high-quality carbon disclosure will guide them to apply digital technology to energy conservation, emission monitoring and clean production, amplify the environmental benefits of digital transformation, and strengthen the carbon reduction effect of digitalization. Accordingly, we propose the third hypothesis:

Hypothesis H3: Carbon disclosure quality plays a positive moderating role in the

relationship between digital transformation and carbon emission reduction of manufacturing firms.

3. Research Design

3.1. Sample and Data

This study takes China's A-share listed manufacturing firms from 2011 to 2022 as the initial sample. We process the sample as follows: (1) Exclude firms with ST and *ST status during the sample period; (2) Exclude samples with missing key data; (3) Winsorize all continuous variables at the 1% and 99% quantiles to avoid the interference of extreme outliers. Finally, we obtain 11,251 firm-year observations of 1,133 firms.

The data sources are as follows: The digital transformation index is obtained by Python text analysis of the annual reports of listed firms; green patent data comes from CNRDS database; financial and corporate governance data comes from CSMAR database.

3.2. Model and Variables

To investigate the effect of digital transformation on corporate carbon emission intensity, this study employs a panel data model that includes firm, industry, and year fixed effects to mitigate omitted variable bias as comprehensively as possible. Additionally, to address potential heteroskedasticity and serial correlation issues, robust standard errors clustered at the firm level are used in all regressions. The benchmark regression model is as follows:

$$Ce_{i,t} = \beta_0 + \beta_1 Dig_{i,t} + \beta_2 Controls_{i,t} + \varphi_t + \mu_j + \lambda_i + \varepsilon_{i,t} \quad (1)$$

Here, i, t, and j represent the firm, year, and industry, respectively. β_0 denotes the constant term. The dependent variable Cei,t indicates the carbon emission intensity of firm i in year t. The core explanatory variable Digi,t represents the digital transformation level of firm i in year t. Controlsi,t denotes the set of control variables, φt represents the time fixed effect, μj denotes the industry fixed effect, λi indicates the firm fixed effect, and εi,t is the error term.

To examine the mediating effects of resource allocation efficiency (TFP) and green technological innovation (Gi), we adopt the causal steps approach following Baron and Kenny (1986). The models are specified as follows:

$$Mediator_{i,t} = \alpha_0 + \alpha_1 Dig_{i,t} + \alpha_2 Controls_{i,t} + \varphi_t + \mu_j + \lambda_i + \varepsilon_{i,t} \quad (2)$$

$$Ce_{i,t} = \gamma_0 + \gamma_1 Dig_{i,t} + \gamma_2 Mediator_{i,t} + \gamma_3 Controls_{i,t} + \varphi_t + \mu_j + \lambda_i + \varepsilon_{i,t} \quad (3)$$

Here, Mediatori,t represents the mediating variables: resource allocation efficiency (proxied by TFP) and green technological innovation (Gi).

To test the moderating effect of carbon disclosure quality (proxied by the Carbon Disclosure Index, CDI), the following model is constructed:

$$Ce_{i,t} = \theta_0 + \theta_1 Dig_{i,t} + \theta_2 CDI_{j,t} + \theta_3 (Dig_{i,t} \times CDI_{j,t}) + \theta_4 Controls_{i,t} + \varphi_t + \mu_j + \lambda_i + \varepsilon_{i,t} \quad (4)$$

The definition of main variables is shown in Table 1.

Table 1. Variable Definitions.

Variable Type	Variable Name	Symbol	Definition
Dependent Variable	Corporate Carbon Emission Level	Ce	Carbon emissions / (Operating revenue / 10,000)
Explanatory Variable	Digital Transformation	Dig	Ln(1+digitalization keyword frequency)
Mediating Variables	Resource Allocation Efficiency	TFP	TFP calculated by LP method
	Green Technological Innovation	Gi	Ln(1+green patent applications)
Moderating Variable	Carbon Disclosure Index	CDI	Ln(carbon disclosure checklist score)
Control Variables	Firm Size	Size	Ln(total assets)
	Leverage	Lev	Total liabilities / Total assets
	Return on Assets	ROA	Net profit / Total assets
	Asset Turnover Ratio	Tat	Operating revenue / Total assets

3.3. Descriptive Statistics

The mean value of Ce is 0.319 (SD=0.487), showing significant differences in carbon emission intensity among sample firms. The mean value of Dig is 1.394 (SD=1.314), indicating an unbalanced digital transformation process. The correlation test shows that Dig and Ce are significantly negatively correlated at 1% level, with no serious multicollinearity.

4. Empirical Results

4.1. Benchmark Regression

Table 2 reports the benchmark regression results. The coefficient of Dig is -0.0082, significantly negative at 1% level, indicating that digital transformation significantly reduces manufacturing firms' carbon emission intensity. Hypothesis 1 is verified.

Table 2. Benchmark Regression Results

	Ce
Dig	-0.0082***
	(-4.49)
Controls	Y
Stkcd/Ind/Year	Y
N	11250
R2	0.9691

Note: *** p<0.01, t-values in parentheses.

4.2. Robustness and Endogeneity

We conduct a series of robustness checks: replacing the core explanatory variable, excluding 2020 sample and first-tier city samples, adding city×year fixed effects, and using one-period lag of Dig to alleviate reverse causality. All results show that the

coefficient of Dig remains significantly negative at 1% level, and the core conclusion is highly robust.

4.3. Mechanism Test

Table 3 reports the mediating effect results. For the resource allocation path, Dig has a significantly positive effect on TFP (1% level), and TFP has a significantly negative effect on Ce (5% level). For the green innovation path, Dig has a significantly positive effect on Gi (1% level), and Gi has a significantly negative effect on Ce (5% level). Both paths are verified, and Hypothesis 2 holds.

Table 3. Mediating Effect Results

	(1)	(2)	(3)	(4)	(5)
	Ce	TFP	Ce	Gi	Ce
Dig	-0.0082***	0.0123***	-0.0080***	0.0318***	-0.0080***
	(-4.49)	(3.25)	(-4.35)	(3.31)	(-4.43)
TFP			-0.0195**		
			(-2.30)		
Gi					-0.0062**
					(-2.06)
Controls	Y	Y	Y	Y	Y
Stkcd/Ind/Year	Y	Y	Y	Y	Y
N	11250	11250	11250	11250	11250
R2	0.9691	0.9783	0.9691	0.6953	0.9691
Adj.R2	0.9655	0.9758	0.9655	0.6601	0.9655

Note: *** p<0.01, t-values in parentheses.

4.4. Further Analysis

The moderating effect test shows that the coefficient of Dig×CDI is -0.0032, significantly negative at 1% level, indicating that higher carbon disclosure quality strengthens the carbon reduction effect of digital transformation. Hypothesis 3 is verified.

Heterogeneity analysis shows that: the carbon reduction effect is more significant in non-state-owned firms, eastern and western regions, and non-heavy-polluting firms.

5. Conclusions and Recommendations

5.1. Conclusions

This study finds that digital transformation has a significant inhibitory effect on the carbon emission intensity of manufacturing firms, with the effect realized through improving resource allocation efficiency and promoting green technology innovation. High-quality carbon disclosure can amplify the carbon reduction effect of digital transformation, and the effect is heterogeneous across firm ownership, region and pollution attributes.

5.2. Recommendations

First, strengthen the construction of industrial digital infrastructure, and guide manufacturing firms to apply digital technologies to achieve precise energy consumption management and low-carbon production. Second, implement targeted incentive policies to support manufacturing firms to improve resource allocation efficiency and carry out green technology innovation through digital transformation. Third, improve the mandatory carbon disclosure system, and strengthen the external supervision of firms' low-carbon behavior.

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