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A Study on the Impact of Digital Transformation on Carbon Emissions Reduction Performance in Export-Oriented Manufacturing Enterprises: An Empirical Analysis Based on Listed Company Data

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Abstract: Driven by the 'Dual Carbon' goals, reducing carbon emissions has become a consensus amongst enterprises. As an emerging economic model, the digital economy—with its characteristics of efficiency, intelligence and innovation—is emerging as a key driver of carbon emission reductions. Export-oriented manufacturing enterprises, as key producers facilitating the integration of the Chinese economy into global value chains, are crucial to the realisation of the 'Dual Carbon' goals. Given that China's digital transformation began in 2011 and the availability of relevant data, this study utilises panel data from 1,093 listed export-oriented manufacturing enterprises in China between 2012 and 2021 to examine the impact of digital transformation on their carbon emission reduction performance. The findings reveal that: (1) export-oriented manufacturing enterprises have enhanced their carbon emission reduction performance through digital transformation; (2) Green technological innovation and factor allocation efficiency act as mediating variables, whilst environmental regulations can dampen the positive impact of digital transformation on carbon emission reduction performance; (3) The driving effect of digital transformation on the carbon emission reduction performance of export-oriented manufacturing enterprises varies across regions. Based on these findings, targeted recommendations are proposed from both the government and enterprise perspectives to better facilitate enterprises' green transformation and green innovation, thereby further enhancing their carbon emission reduction performance.

Keywords: Digital transformation, carbon emission reduction performance, manufacturing, export-oriented enterprises.

1. Introduction

As the issue of global warming becomes increasingly severe, the international community is calling ever more strongly for climate governance. As a responsible major power, China has actively responded to these calls by setting the target of 'reaching carbon peak by 2030 and achieving carbon neutrality by 2060'.The manufacturing sector constitutes a vital component of China's industrial and supply chain systems, whilst also representing a key area in terms of energy and resource consumption and carbon emissions; promoting carbon emission reductions in manufacturing is therefore of significant importance for achieving the 'dual carbon' goals. Against the backdrop of these goals, the 14th Five-Year Plan further emphasises the need to accelerate the green transformation of development models, actively promote the digitalisation of manufacturing, and foster the deep integration of the digital economy with the real economy. Green and low-carbon development has become a new trend in China's manufacturing sector. The 'Opinions on Accelerating the Comprehensive Green Transformation of Economic and Social Development' issued by the Central Committee of the Communist Party of China and the State Council emphasise the need to deepen the application of digital technologies to empower the green transition. Digital transformation is a key means of enabling manufacturing enterprises to reduce carbon emissions and achieve high-quality development. A thorough investigation into the mechanisms through which digital transformation influences carbon emissions in manufacturing enterprises is of great significance for promoting low-carbon development and green transformation within the sector.

In the era of the digital economy, the digital transformation of the manufacturing sector can drive green technological innovation and improve the efficiency of resource allocation, thereby enhancing carbon emission efficiency and achieving digital carbon reduction. Existing research in this area has largely focused on export-oriented enterprises in specific sectors such as furniture, textiles and automotive; however, the mechanisms through which digital transformation contributes to carbon reduction across the export manufacturing sector as a whole have not yet been sufficiently explored. To address this research gap, this paper takes export-oriented manufacturing enterprises as its subject, constructs an analytical framework featuring dual mediation by green technological innovation and factor allocation efficiency, introduces environmental regulation as a moderating variable, and verifies the multiple pathways through which digital transformation promotes carbon emission reductions. Furthermore, heterogeneity analysis is conducted from the perspectives of pollution intensity and geographical distribution to elucidate the distinctive characteristics of carbon emission reduction performance across different types of enterprises. This study holds significant practical value. For export-oriented manufacturing enterprises deeply involved in global industrial chain competition, it helps to clarify the direction of digital investment, establish a digital carbon emissions management system, formulate carbon emission reduction strategies aligned with international environmental standards, effectively address green trade barriers such as carbon tariffs, and forge a differentiated competitive advantage through green transformation. For policy-making bodies, the research

findings can provide theoretical support for the formulation of relevant policies, guiding the export manufacturing sector to advance digital transformation and carbon emission reduction targets in tandem, thereby contributing to green and low-carbon socio-economic development.

2. Literature Review

With the widespread application of digital technologies, the empowering effects of the digital economy have become increasingly evident. The central government has attached great importance to this and implemented a series of measures, whilst the digital transformation of enterprises has emerged as a hot topic in academic research. Existing research focuses on its definition, measurement and influencing factors; the academic community generally regards digital transformation as a systemic transformation encompassing business processes, organisational structures and business models, although no unified consensus has yet been reached on its precise definition. Liu Donghui et al. (2022) point out that digital transformation promotes organisational change and enhances operational efficiency and organisational performance through the integration of next-generation digital technologies with corporate business processes and services [Liu Donghui et al, 2022]. Yao Xiaotao et al. (2022) also emphasise that the core of digital transformation lies in utilising digital technologies to trigger significant changes in organisational attributes, thereby achieving organisational improvement [Yao Xiaotao et al., 2022]. The objective data method measures the extent of a company's digital transformation by calculating its investment in this area; the event-driven method assesses a company's digital transformation status based on whether it has been affected by relevant policies; and the lexical method quantifies the level of transformation by analysing the frequency of digital keywords in the company's annual reports.Hu Yuanlin and Zhuang Yongyao (2023) argue that the factors influencing a company's digital transformation can be broadly categorised into external and internal factors. External factors include environmental changes, shifts in consumer behaviour and industry differences, whilst internal factors encompass the company's transformation objectives, resources and capabilities, as well as whether the company possesses the necessary conditions for transformation [Hu Yuanlin & Zhuang Yongyao, 2023]. Furthermore, digital transformation can enhance a firm's innovation capacity and total factor productivity, whilst improving the efficiency of investment and financing; it significantly influences corporate performance through pathways such as efficiency gains, cost reductions and the driving of innovation.

With regard to research on carbon emissions reduction, the existing literature primarily explores the influencing factors and pathways for emissions reduction. Scholars have found that carbon emissions are influenced by a variety of factors, including the level of economic development, industrial structure, digital transformation and energy mix. Wang Jing and He Huijuan (2024) point out that economically developed, high-carbon-emission-intensity and coastal regions are better positioned to achieve carbon emissions reduction through participation in the 'dual circulation' strategy [Wang Jing & He Huijuan, 2024]. Gao Zhigang et al. (2024) point out that optimising industrial structure can significantly curb carbon emissions, achieving a decoupling of economic growth from carbon emissions by enhancing the sophistication and rationalisation of industries [Gao Zhigang et al., 2024]. Li Congxin and Liu Jiayuan (2024), meanwhile, emphasise that the rise of the digital economy has a positive impact on carbon emission reductions by improving energy efficiency and promoting green technological innovation [Li Congxin & Liu Jiayuan, 2024]. Furthermore, Sun Wanlin et al. (2025) argue that rising energy costs are a key driver of carbon emissions reductions in the industrial sector [Sun Wanlin et al., 2025]. Corporate carbon emissions reductions are primarily achieved through technological innovation, policy guidance, industrial restructuring and the optimisation of the energy mix. Liu Yiwén et al. (2025) found that smart manufacturing significantly reduces corporate carbon emissions by improving energy efficiency and promoting green technological innovation [Liu Yiwén et al., 2025]. Lü Hongjun and Wei Xiuxiu (2025) further pointed out that digital transformation not only directly promotes carbon emission reductions but also indirectly drives them through green technological innovation; moreover, the digital transformation of enterprises within supply chain networks has demonstrated significant spillover effects in terms of carbon emission reductions [Lü Hongjun&Wei Xiuxiu, 2025].

Against the historical backdrop of the rapid development of digital technologies and the 'dual carbon' goals, digital transformation has become a key factor in driving productivity growth, reducing energy consumption and achieving sustainable development. Through digital transformation, enterprises can optimise production processes and energy management systems, thereby enhancing their energy efficiency. Yang Pengyu et al. (2024) emphasise that digital transformation provides strong support for enterprises' green technological innovation; through digital platforms, enterprises can integrate R&D resources more efficiently, accelerate the research, development and application of green technologies, and drive the transition of products and services towards low-carbon models [Yang Pengyu et al., 2024]. Wang Jun et al. (2025) point out that, given the heterogeneity in the effects of digital transformation on carbon emissions reduction across different industries and regions, it is necessary to formulate differentiated policy measures [Wang Jun et al., 2025]. He Li (2025), on the other hand, notes that whilst digital transformation plays a positive role in carbon emissions reduction, it also faces challenges such as high technological costs, data security and privacy protection issues [He Li, 2025].

Existing research suffers from two limitations: firstly, it tends to focus on the manufacturing sector as a whole or on regional economies, with insufficient attention paid to the specific group of export-oriented manufacturing enterprises; secondly, whilst some studies have examined the mediating role of green technological innovation, few have incorporated it into a unified analytical framework alongside factor allocation efficiency. Consequently, this paper takes China's export-oriented manufacturing enterprises as its subject of study and constructs a dual-mediation theoretical framework examining the impact of digital transformation on carbon emission reduction performance, introducing environmental regulation as a moderating variable. The aim is to elucidate the direct effects of digital transformation, the dual-mediation transmission pathways, and the moderating role of environmental regulation.

3. Theoretical Framework and Research Hypotheses

3.1. The Direct Impact of Digital Transformation on The Carbon Emission Reduction Performance of Export-Oriented Manufacturing Enterprises

In the era of the digital economy, manufacturing export enterprises can achieve carbon emissions reductions across the entire process and optimise international trade supply chains through digital transformation. In the procurement phase, big data is utilised to precisely match green suppliers and optimise low-carbon logistics routes; in the production phase, the Industrial Internet is leveraged to enhance energy efficiency; in the research and development phase, digital technologies are employed to accelerate the iteration of low-carbon products; in the sales phase, cross-border e-commerce is utilised to reduce carbon emissions in the distribution chain; and in the operations phase, blockchain technology is utilised to enable carbon footprint traceability, thereby meeting international carbon tariff compliance requirements. Based on the resource-based view and the theory of technology empowerment, digital technologies reshape enterprises' low-carbon competitiveness across three dimensions—the Internet of Things, artificial intelligence and blockchain—shortening the innovation cycle for low-carbon processes and creating a virtuous cycle of digital emissions reduction and export premiums. Digital transformation not only reduces emissions at the production stage but also helps enterprises address green trade barriers such as the EU's Carbon Border Adjustment Mechanism. By aligning with international carbon standard certifications through digital carbon accounting, it achieves a dual improvement in environmental performance and export competitiveness. On this basis, this paper proposes Research Hypothesis 1:

Hypothesis 1: Digital transformation can drive carbon emission reductions in export-oriented manufacturing enterprises.

3.2. The Mechanism Through Which Digital Transformation Influences Carbon Emission Reduction Performance in Export-Oriented Manufacturing Enterprises

Digital transformation drives carbon emission reductions indirectly by enhancing production management efficiency, optimising supply chain transparency and promoting green technological innovation. Technologies such as the Internet of Things (IoT), big data, cloud computing and artificial intelligence (AI) enable real-time monitoring and optimisation of energy consumption and emissions during production. Green technological innovation reduces greenhouse gas emissions through new materials and processes. Faced with stringent international market requirements for low-carbon products, export-oriented manufacturing enterprises rely on digitalisation and green technological innovation to reduce their carbon footprint, thereby enhancing their market competitiveness. Based on this, this paper proposes Research Hypothesis 2:

Hypothesis 2: Digital transformation, aided by green technological innovation, can help export-oriented manufacturing enterprises reduce carbon emissions.

By improving the efficiency of resource allocation, digital transformation has become key to achieving low-carbon development in export-oriented manufacturing. Digital technologies optimise production processes, reduce energy wastage and improve resource utilisation, thereby lowering carbon emissions without reducing output. Digital platforms monitor carbon emissions data in real time, helping enterprises formulate effective emission reduction strategies, meet international environmental standards, and enhance competitiveness. Consequently, digital transformation provides export-oriented manufacturing enterprises with technical support and management solutions, driving the achievement of carbon emission reduction targets. Accordingly, this paper proposes Research Hypothesis 3:

Hypothesis 3: Digital transformation drives carbon reduction efforts in export-oriented manufacturing enterprises by improving the efficiency of factor allocation.

Environmental regulations are laws, policies and standards established by the government to protect the environment, aimed at curbing enterprises' negative environmental impacts and promoting sustainable development. However, stringent environmental regulations force export-oriented manufacturing enterprises to invest substantial resources in meeting emission standards, potentially leading them to prioritise compliance investments over digital transformation, thereby limiting the role of digital transformation in carbon emission reduction. Furthermore, it takes a relatively long time for digital transformation to yield carbon emission reduction benefits, whereas the pressure from environmental regulations is typically short-term. This may lead enterprises to favour short-term emission reduction measures with immediate, tangible results, whilst overlooking the potential of digital transformation to reduce carbon emissions in the long term. Taking both aspects into account, this paper proposes Research Hypothesis 4:

Hypothesis 4: Environmental regulations exert a inhibitory effect on the role of digital transformation in promoting carbon emission reductions among export-oriented manufacturing enterprises.

3.3. Variations in the Impact of Digital Transformation on The Carbon Emission Reduction Performance of Export-Oriented Manufacturing Enterprises

As the foundation of digital innovation, digital infrastructure enables precise benchmarking of carbon emission reductions across regions through technological penetration. The eastern region, with its high level of economic developmentand the clustering of energy-intensive industries such as steel and chemicals, boasts well-developed and comprehensive digital infrastructure, achieving near-universal coverage of 5G networks and industrial internet platforms. Enterprises in these regions are able to utilise technologies such as big data and the Internet of Things more efficiently to optimise energy management, promote industrial chain collaboration and achieve targeted emissions reductions. In contrast, industries in central and western regions are dispersed and constrained by insufficient investment in digitalisation and a shortage of technical talent; as a result, technology penetration rates are low and the marginal benefits of digitalised collaborative emissions reduction are weak. Consequently, this paper proposes Research Hypothesis 6:

Hypothesis 5: The driving effect of digital transformation

on the carbon emission reduction performance of export-oriented manufacturing enterprises varies across regions.

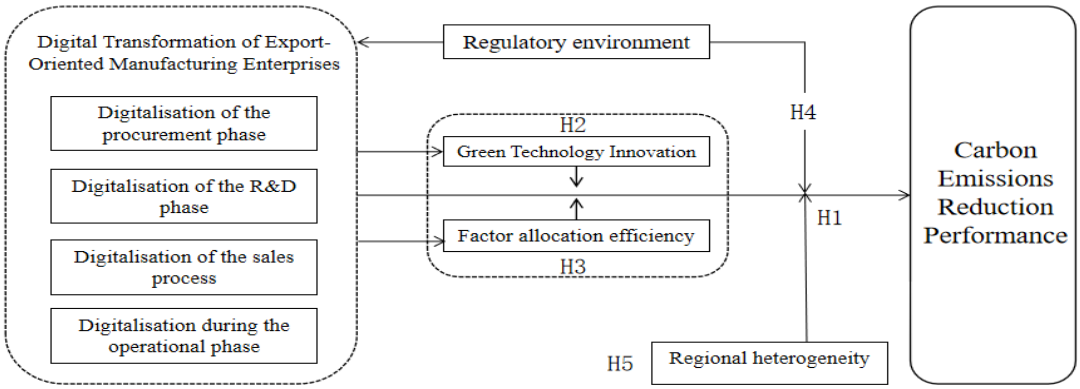

Figure 1. Diagram illustrating the mechanism of the impact of digital transformation on the carbon emission reduction performance of export-oriented manufacturing enterprises

4. Empirical Design

4.1. Model Construction

4.1.1. Baseline Regression Model

To investigate the impact of digital transformation on the carbon emission reduction performance of export-oriented manufacturing enterprises, the following model was constructed:

$$Cerp_{it} = \alpha_0 + \alpha_1 DIG_{it} + \sum \alpha_k Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} (1)$$

Where the dependent variable is carbon emission reduction performance, denoted by Cerp; the core independent variable is the degree of digital transformation, denoted by DIG; Control represents the set of control variables; μ_i denotes firm-level fixed effects; λ_t denotes year-level fixed effects, controlling for factors that do not vary over time at the firm level and factors that do not vary across firms at the year level; ε_{it} denotes the random error term, with the subscript i denoting the firm and t denoting the year.

4.1.2. Mediation Effect Model

Building upon Equation (1), the following mediation model is constructed to test the mediating effects of green technological innovation (Green) and factor allocation efficiency (Produce), where M denotes the mediating variable:

$$M_{it} = \beta_0 + \beta_1 DIG_{it} + \sum \beta_k Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

$$Cerp_{it} = \gamma_0 + \gamma_1 DIG_{it} + \gamma_2 M_{it} + \sum \gamma_k Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

4.1.3. Moderation Effect Model

To test Hypothesis 4, building upon the model (1) presented in this paper, we introduce the interaction term DIG×ER between the variables 'digital transformation' (DIG) and 'regulatory environment' (ER), and construct a model to test the moderating effect of the regulatory environment, as shown in Equation (4).

$$Cerp_{i,t} = \omega_0 + \omega_1 DIG_{i,t} + \omega_2 ER_{i,t} + \omega_3 DIG_{i,t} \times ER_{i,t} + \sum \omega_k Control_{i,t} + \mu_t + \lambda_t + \varepsilon_{i,t} \quad (4)$$

4.2. Variable Descriptions

(1) Dependent variable: carbon emission reduction performance (Cerp). As companies rarely disclose their carbon dioxide emissions, this study adopts the measurement method proposed by Li Wanhong (2023) [Li Wanhong et al., 2023] and others, this study collects data on sectoral carbon emissions from the CEADs database. Sector-specific costs of main business operations are obtained from the key financial indicators (by sector) for enterprises above a certain scale, as disclosed on the National Bureau of Statistics' official website. This data is then used to estimate corporate carbon emissions. Revenue per unit of carbon emissions serves as a proxy variable for carbon emission reduction performance (Cerp); a higher value of this indicator indicates better carbon emission reduction performance. The formula for carbon emission reduction performance is shown below:

$$Cerp = \frac{MR}{\left(\frac{MCO_2}{MCB}+1\right)\times MC} \quad (5)$$

(2) Explanatory variable: Digital transformation (DIG) of manufacturing enterprises. Drawing on the methodology of Wu Fei (2021) [Wu Fei et al., 2021], this study uses the frequency of terms related to 'enterprise digital transformation' mentioned in the annual reports of listed manufacturing enterprises as a proxy indicator to measure the degree of digital transformation.

(3) Mediating variables: Green technological innovation (Green). This study uses the sum of green invention and utility model applications plus one, taken to the logarithm, to indirectly characterise the level of a firm's green technological innovation; factor allocation efficiency (Produce). Drawing on the approach of Huang Dayu (2022) [Huang Dayu et al., 2022], total factor productivity is used as a proxy for factor allocation efficiency, and the LP estimation method is employed to measure firms' factor allocation efficiency.

(4) Moderating variable: Regulatory environment (ER). Following the approach of Liu Chang (2023) [Liu Chang et al., 2023], the regulatory environment is measured as the proportion of the listed company's location's expenditure on air and wastewater pollution control in the given year relative to its industrial output value for that year.

(5) Control variables: Taking into account factors influencing corporate carbon emissions reduction, this study draws on the research of Fang Lan et al. (2022) [Fang Lan et al., 2022] and Liu Hui (2022) et al. [Liu Hui et al., 2022], this study selects the following control variables: firm age (FirmAge), Tobin's Q (TobinQ), cash flow ratio (Cashflow), debt-to-asset ratio (Lev), operating efficiency (ATO), administrative expenses (Mfee), funds tied up by major shareholders (Occupy), and growth (Growth).

4.3. Data Sources

This paper takes A-share-listed manufacturing enterprises as its initial sample, excluding those classified as ST, *ST, delisted companies, and those with significant missing key data. Exporting enterprises were identified by filtering the sample based on fields such as 'overseas' and 'exports' in the 'operating revenue segments' section of the CSMAR database. The study period spans 2012-2021, resulting in a final sample of 1,093 companies comprising 10,551 observations. Outliers were removed by trimming the top and bottom 1 per cent of continuous variables. Regarding data sources, economic and financial data were obtained from the Wind and CSMAR databases; patent-related data were sourced from the CNRDS database; digital transformation indicators were extracted through text analysis of listed companies' annual reports; and a small amount of missing data was supplemented via specialist platforms such as the Juchao Information Network.

5. Empirical Analysis

5.1. Descriptive Statistics of Variables

First, a descriptive statistical analysis was conducted on the data for each variable. As shown in Table 1, the maximum value for carbon emission reduction performance was 50.88 and the minimum was 37.18, indicating a marked difference; simultaneously, there were significant variations in the level of corporate digital transformation, with a maximum value of 4.727 and a minimum of 0; furthermore, there were substantial differences in Tobin's Q, ATO and Mfee, suggesting that the sample used in this study is well-balanced.

Table 1. Descriptive statistics for each variable

Variable	Observations	Mean	Standard Deviation	Minimum	Maximum
Cerp	10,551	43.08	2.861	37.18	50.88
DIG	10,551	1.218	1.266	0	4.727
FirmAge	10,551	2.901	0.321	1.946	3.497
TobinQ	10,551	2.049	1.206	0.876	7.394
Cash flow	10,551	0.0492	0.0612	-0.124	0.219
Lev	10,551	0.414	0.190	0.0593	0.859
ATO	10,551	0.659	0.356	0.119	2.126
Mfee	10,551	0.296	1.233	0	10.53
Occupy	10,551	0.0120	0.0178	0.000169	0.114
Growth	10,551	0.148	0.320	-0.469	1.740

Note: Calculated using Stata 18.0; the same applies below.

5.2. Multicollinearity Test

In order to analyse and investigate the intrinsic relationships between the variables and the dependent variable in a more scientific manner, a VIF analysis was conducted using Stata 18.0. Specifically, the higher the VIF value, the more severely the variance of that variable is inflated due to multicollinearity. Generally, a VIF value greater than 10 is considered an indication of severe multicollinearity, which may require further treatment. Conversely, a VIF value less than 10 indicates that the model can be used as is. As shown in Table 2. The table reveals that the VIF value between the dependent variable and the independent variables is 1.08, indicating that the regression model does not suffer from multicollinearity and can be used as is.

Table 2. VIF calculation results

Variable	VIF	1/VIF
DIG	1.02	0.982054
ATO	1.10	0.906520
TobinQ	1.10	0.911227
Cashflow	1.10	0.912488
FirmAge	1.06	0.940123
Occupy	1.06	0.947606
Growth	1.03	0.975507
Lev	1.22	0.822686
Mfee	1.01	0.991260
Mean VIF	1.08	

5.3. Analysis of Baseline Regression Results

This paper first conducts a VIF test; as the VIF is less than 2, there is no multicollinearity among the variables. Secondly, a Hausman test is carried out; the results reject the null hypothesis, and therefore a fixed-effects model is selected. Regression analysis of the econometric model was performed using Stata 18.0, and the results are presented in Table 3.

As can be seen from the table above, Column (1) includes only the core explanatory variables and the dependent variable, with firm and year held constant; no other control variables have been included. The table shows that the relationship between digital transformation and carbon emission reduction performance in manufacturing enterprises is significantly positive at the 1 per cent level, indicating a significant positive correlation between the two. This suggests that digital transformation in export-oriented manufacturing enterprises has a significant positive impact on carbon emission reduction performance. Column (2) further tests this relationship by including various control variables whilst holding firm and year constant. As shown in the table, the relationship between digital transformation and carbon emission reduction performance in manufacturing enterprises remains significantly positive at the 1% level, indicating a significant positive correlation between the two. This demonstrates that digital transformation in manufacturing enterprises can enhance carbon emission reduction performance, thereby validating Hypothesis 1.

Table 3. Regression Analysis

Variables	Cerp (1)	Cerp (2)
DIG	0.146***	0.115***
	(11.082)	(10.229)
FirmAge		0.969***
		(9.356)
TobinQ		-0.136***
		(-14.337)
Cashflow		0.714***
		(4.631)
Lev		2.139***
		(28.563)
ATO		1.526***
		(35.845)
Mfee		-0.006
		(-0.818)
Occupy		-1.894***
		(-3.582)
Growth		0.426***
		(16.828)
_cons	41.999***	37.739***
	(1528.385)	(137.838)
N	10551	10551
R^2	0.391	0.553
Time effect	Yes	Yes
Individual effect	Yes	Yes

Note: ***, ** and * denote significance at the 1 per cent, 5 per cent and 10 per cent levels respectively; figures in brackets represent standard deviations; the same applies throughout.

5.4. Robustness Tests and Endogeneity Tests

This paper conducted robustness tests in the following two aspects: (1) by excluding the 2020 and 2021 samples from the pandemic period; if the model results remain consistent, this indicates that the findings of this paper are relatively stable; (2) Drawing on the methods of Zhao Chenyu (2021) [Zhao Chenyu et al., 2021], we recalculated the digital transformation variable, denoted as DIG2, and substituted the recalculated values of the core explanatory variables for the original ones, incorporating them into the model using the original empirical analysis methodology. As can be seen from the data in the table below, the coefficient of influence of DIG on the dependent variable is 0.110, which passes the test at the 1 per cent significance level; the coefficient of influence of DIG2 is 13.692, which is also significant at the 1 per cent significance level. This result is consistent with the conclusions presented earlier, confirming the robustness of the empirical analysis in this paper.

To eliminate endogeneity issues arising from potential interactions between the explanatory variable, digital transformation (DIG), and the dependent variable, this paper employs the instrumental variables method for estimation. Specifically, the one-period lag of digital transformation (DIG), denoted as l. DIG, is set as the instrumental variable to ensure independence between the explanatory variable and the error term. As shown in Table 4, the coefficient of the one-period lag of digital transformation on carbon emission performance is 0.118, which is significant at the 1 per cent significance level. Therefore, even when endogeneity is taken into account, the positive impact of digital transformation (DIG) on corporate carbon emission performance remains quite evident.

Table 4. Robustness Tests and Endogeneity Tests

Variables	Exclusion of exceptional years		Changing the estimation method		One-period lag of the explanatory variable	
	Cerp	Cerp	Cerp	Cerp	Cerp	Cerp
DIG	0.139***	0.110***				
	(10.227)	(9.447)				
DIG2			15.715***	13.692***		
			(13.386)	(13.565)		
l.DIG					0.125***	0.118***
					(5.440)	(6.075)
_cons	42.024***	38.475***	41.998***	37.764***	42.257***	38.115***
	(1695.846)	(146.188)	(1544.260)	(138.522)	(1223.784)	(61.916)
Control variables	No	Yes	No	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes	Yes	Yes
Individual effects	Yes	Yes	Yes	Yes	Yes	Yes
N	8444	8444	10551	10551	9457	9457
R^2	0.368	0.537	0.394	0.557	0.364	0.532

5.5. Mechanism testing

5.5.1. Mediating Effects

Using Model (4-2) to examine the relationships between digital transformation in manufacturing enterprises, green technological innovation and factor allocation efficiency, Table 5 presents the results of the mediation effect tests for green technological innovation and factor allocation efficiency in the relationship between digital transformation in manufacturing enterprises and carbon emission reduction performance. The results indicate that the regression coefficients for DIG with Green and Produce are 0.0263 and 0.0304 respectively, both significant at the 1% level, demonstrating that the digital transformation of manufacturing enterprises promotes green technological innovation and factor allocation efficiency; Model (4-3) incorporates the Green and Produce variables in addition to those in Model (4-2),The results show that the regression coefficients for Green and Produce relative to Cerp are 0.0719 and 2.004 respectively, and are significant at the 1% level; the regression coefficients for DIG relative to Cerp are 0.114 and 0.0545 respectively, and are significant at the 1% level. This

indicates that green technological innovation and factor allocation efficiency play a mediating role in the impact of digital transformation in manufacturing enterprises on carbon emission reduction performance, thereby validating Hypotheses 2 and 3.

Table 5. Mediating Effects

Variables	Green technological innovation		Factor allocation efficiency	
	Green	Cerp	Produce	Cerp
DIG	0.0263***	0.114***	0.0304***	0.0545***
	(3.45)	(10.07)	(7.93)	(6.57)
Green		0.0719***		
		(4.73)		
Produce				2.004***
				(90.48)
_cons	0.180	37.73***	4.320***	29.08***
	(0.98)	(137.94)	(46.41)	(130.95)
Control variables	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes
N	10551	10551	10551	10551

5.5.2. Moderating Effect

Table 6. Moderating effect

Variables	Cerp (1)	Cerp (2)
DIG	0.115***	0.110***
	(10.23)	(9.69)
ER		0.005
		(0.74)
DIG×ER		-0.018***
		(-4.22)
_cons	37.739***	37.765***
	(137.84)	(137.89)
Control variables	Yes	Yes
Fixed effects	Yes	Yes
N	10,551	10,551
R^2	0.553	0.554

Using Equation (4), we introduced environmental regulation as a moderating variable to examine its moderating effect on the relationship between digital transformation and corporate carbon emission reduction performance. The regression results are shown in Table 6. As can be seen from the table, the coefficient of the interaction term between environmental regulation and digital transformation is –0.018 and is significant at the 1 per cent level. This result may be attributed to the following: on the one hand, both digital development and environmental regulation can effectively improve carbon emission performance; however, the synergistic effect between digitalisation and environmental regulation is poor, meaning that environmental regulation weakens the positive impact of digitalisation on carbon emission performance [Shang Shu & Feng Langang, 2024]; on the other hand, a review of existing research reveals that digital development is more effective at 'carbon control' in high-carbon regions than in low-carbon regions. Environmental regulation can effectively control carbon emissions; regions with stricter environmental regulations have lower carbon emissions, whilst those with more lenient regulations have higher carbon emissions [Li Jing et al., 2021]. Therefore, environmental regulation negatively moderates the 'carbon control' effect of digitalisation. The research findings support the conclusion that environmental regulations negatively moderate the effect of digitalisation on carbon emission performance.

5.6. Heterogeneity Test

To examine whether the impact of digital transformation on carbon emission reduction performance varies across different regions, this paper divides the sample into three groups—Western, Central and Eastern—based on the geographical location of the manufacturing enterprises. The regression results are shown in the table below:

Table 7. Test of Regional Heterogeneity

Variables	Western Region	Central Region	Eastern Region
	Cerp	Cerp	Cerp
DIG	0.045	0.070**	0.113***
	(1.170)	(2.496)	(7.882)
_cons	35.465***	38.636***	37.750***
	(32.831)	(54.830)	(127.040)
Control effect	Yes	Yes	Yes
Time effect	Yes	Yes	Yes
Individual effects	Yes	Yes	Yes
N	1358	1862	5486
R^2	0.431	0.537	0.615

Tests for regional heterogeneity revealed that the digital transformation coefficients for export-oriented manufacturing enterprises in the eastern and central regions were 0.113 and 0.07 respectively, which were significant at the 1 per cent and 5 per cent levels respectively; the coefficient for the western region was 0.45 and did not pass the significance test. The eastern region, characterised by rapid development of the digital economy and a concentration of high-carbon industries, has achieved the most notable results in terms of digital emissions reduction; the central region, having embarked on its transformation earlier, has already partially realised its emissions reduction potential; whilst the western region, with its weak foundation in the digital economy, has yet to fully realise the carbon reduction benefits of its transformation.

6. Conclusions and Recommendations

Digital transformation is a key pathway for China to achieve its carbon peak and carbon neutrality targets. Drawing on a sample of 1,093 listed manufacturing export enterprises, this paper empirically examines the impact of digital transformation on corporate carbon emission reduction performance, analyses the dual-mediation mechanism involving green technological innovation and factor allocation efficiency, explores the moderating role of environmental regulations, and analyses the heterogeneity of emission reduction effects across both industry and region. The findings indicate that digital transformation exerts a significant positive impact on the carbon emission reduction performance of manufacturing export enterprises; firms can leverage digital transformation to promote green technological innovation and enhance the efficiency of factor allocation, thereby strengthening emission reduction outcomes; environmental regulations weaken the positive carbon emission reduction effects of digital transformation to a certain extent; and the eastern region, with its superior

foundation for digital development, demonstrates a more pronounced impact of digital transformation on emission reduction compared to the central and western regions.

To drive the digital transformation of manufacturing export enterprises and facilitate carbon emissions reductions, collaboration between the government and the private sector is required to create a synergistic effect. At the government level, policy support and guidance should be strengthened by establishing a dedicated subsidy fund for digital transformation. Financial support should be provided to enterprises demonstrating outstanding results in areas such as industrial internet development and smart manufacturing demonstration projects. This should be complemented by tax incentives, such as accelerated depreciation for digital equipment and additional tax deductions for research and development expenditure, to reduce the costs of transformation for enterprises. At the same time, efforts should be focused on key areas with targeted measures, including increasing environmental protection funding for heavily polluting export-oriented enterprises and prioritising the digital transformation of enterprises in the eastern regions to drive overall emissions reductions across the sector. At the enterprise level, companies need to formulate phased green digitalisation plans tailored to their industry's specific characteristics, adhering to the principle of 'establishing new systems before dismantling old ones' to steadily advance carbon reduction upgrades and improve green digital management systems; they should proactively engage with policy resources and ensure the proper use of funds; increase investment in digital R&D and deepen collaboration between industry, academia and research institutions; and strengthen talent support through internal skills training and the recruitment of external talent, thereby comprehensively enhancing carbon emission reduction performance.

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