

# Investigating the Impact Mechanism of Corporate Digital Transformation on Carbon Emission Intensity under the Dual Carbon Goals

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**Abstract:** Under the impetus of the dual carbon strategy and the burgeoning digital economy, Chinese enterprises have been rapidly embracing digital transformation, with the adoption rate of digital technologies reaching 47.4% by 2023. Nevertheless, the nuanced interplay between corporate digitalization and carbon emission intensity remains insufficiently understood. Employing panel data from China's A-share listed firms spanning 2010 to 2022, this study systematically investigates how corporate digital transformation shapes carbon emission intensity. Empirical results demonstrate that digital transformation substantially curtails corporate carbon emission intensity, a finding that withstands a battery of robustness checks including the Heckman two-stage correction and propensity score matching. Mechanism analysis further reveals that digital transformation attenuates carbon emission intensity primarily through augmenting R&D expenditure. Heterogeneity tests indicate that this mitigating effect is particularly salient among state-owned enterprises and firms audited by Big Four accounting firms. These findings not only advance scholarly understanding of the determinants of corporate carbon emission intensity but also offer practical implications for leveraging digitalization to foster low-carbon development and the realization of China's dual carbon objectives.

**Keywords:** Corporate Digital Transformation; Carbon Emission Intensity; R&D Investment; Dual Carbon Goals.

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## 1. Introduction

In the context of global green development initiatives and China's vigorous promotion of the digital economy, the Chinese economy is undergoing a rapid transition toward sustainability, efficiency, and innovation. This economic momentum hinges upon industrial upgrading and the establishment of green development paradigms. The "dual carbon" targets—achieving carbon peak by 2030 and carbon neutrality by 2060—have emerged as pivotal strategic objectives that fundamentally reshape the landscape of corporate governance and industrial policy [1]. Concurrently, Chinese enterprises confront the imperative of digital transformation. Although the penetration rate of digital technology applications reached 47.4% in 2023, the complex nexus between corporate digitalization and carbon emission intensity warrants further scholarly inquiry. A substantial number of firms are actively pursuing digital transformation, yet the pathways and magnitude of its impact on carbon emissions remain underexplored. Consequently, elucidating the influence of corporate digital transformation on carbon emission intensity carries considerable theoretical and practical significance for facilitating green, low-carbon development while capitalizing on the dividends of digitalization [2].

The transition to a low-carbon economy represents a fundamental restructuring of industrial production and energy consumption patterns. Historically, China's rapid economic growth relied heavily on energy-intensive and high-emission industries, resulting in substantial environmental externalities. As the world's largest carbon emitter, China's commitment to the dual carbon goals necessitates profound transformations at the microeconomic level, particularly among corporate entities that constitute the primary sources of industrial

emissions. In this transformative era, digital technologies—encompassing artificial intelligence, big data analytics, cloud computing, and the Internet of Things (IoT)—have emerged as critical enablers of industrial upgrading. The integration of these technologies into corporate operations not only redefines business models and value creation processes but also offers unprecedented opportunities for environmental management and resource optimization. The convergence of digital transformation and environmental sustainability thus represents a frontier of both academic inquiry and practical innovation.

Prior scholarship has examined the ramifications of corporate digital transformation across multiple dimensions. From the perspective of firm performance, digitalization has been shown to affect innovation output and production efficiency [3] [4] [5]. From an operational standpoint, digital transformation influences financing constraints [6], total factor productivity [7], and stock price crash risk [8]. Moreover, the literature has documented the role of digitalization in reshaping organizational structures, enhancing information transparency, and facilitating stakeholder engagement. However, the existing body of literature has not adequately addressed the mechanism through which corporate digitalization affects carbon emissions. While some studies have explored the macro-level relationship between digital economy development and regional carbon emissions, firm-level evidence remains scarce and fragmented. This paper therefore seeks to bridge this gap by investigating the relationship between corporate digital transformation and carbon emission intensity at the micro level, providing granular insights that complement existing macro-level analyses.

From a theoretical standpoint, digital transformation may exert countervailing effects on carbon emissions. On one

hand, the process of digitalization entails substantial resource consumption. Enterprises pursuing technological innovation or strategic transformation typically incur significant R&D expenditures and face prolonged investment return cycles, inevitably consuming considerable economic and human resources [9]. Moreover, the restructuring of internal business processes during digital transformation generates exponential data growth, and the storage and processing of such data demand substantial energy inputs, potentially intensifying carbon emissions [10]. The deployment of large-scale data centers and the continuous operation of digital infrastructure require massive electricity consumption, which, if sourced from fossil fuels, could inadvertently exacerbate the corporate carbon footprint. Additionally, the rebound effect—whereby efficiency gains from digitalization lead to increased overall consumption—may partially offset the anticipated emission reductions.

On the other hand, digital transformation may serve as a catalyst for carbon emission reduction through multiple channels. Digital technologies such as big data analytics and artificial intelligence can facilitate more precise R&D planning and accelerate the development of green technologies. Through digital platforms, firms can more efficiently integrate innovation resources and collaborate with research institutions to advance green technology breakthroughs. Additionally, digitalization enhances resource allocation efficiency, enabling more refined production management [11]; optimizes human capital structures conducive to low-carbon strategies; promotes specialized division of labor that improves production efficiency [7]; and enables real-time carbon emission monitoring systems for targeted emission reduction measures. The implementation of smart manufacturing systems allows for the dynamic optimization of energy consumption, minimizing waste and improving overall energy efficiency. Furthermore, digital supply chain management enables firms to track and optimize the carbon footprint across the entire value chain, from raw material sourcing to final product delivery.

Given these dual theoretical possibilities, this study empirically examines the net effect of corporate digital transformation on carbon emission intensity using data from China's A-share listed companies over the period 2010–2022. The findings confirm that digital transformation significantly mitigates corporate carbon emission intensity, and this result remains robust across alternative variable specifications and instrumental variable approaches. The mitigating effect is more pronounced among firms audited by Big Four accounting firms and state-owned enterprises. The mechanism analysis reveals that digital transformation reduces carbon emission intensity by stimulating scientific and technological R&D investment, thereby validating the innovation-driven pathway of emission reduction.

This paper contributes to the literature in three principal ways. First, it enriches the research on the determinants of corporate carbon emission reduction by introducing digital transformation as a novel explanatory factor, thereby complementing the predominantly consequence-oriented literature on the dual carbon economy. Second, it extends the understanding of digital transformation's broader implications by demonstrating its role in environmental governance, offering a fresh perspective grounded in the macro context of the digital economy. Third, by identifying R&D investment as a critical transmission channel, this study provides actionable insights for corporate managers and

policymakers seeking to leverage digitalization for sustainable development. The findings underscore the importance of aligning digital strategy with environmental objectives to achieve synergistic outcomes.

The remainder of this paper is organized as follows: Section 2 reviews the relevant literature; Section 3 presents the research hypotheses and empirical design; Section 4 reports the empirical results and analysis; Section 5 conducts further mechanism and heterogeneity tests; and Section 6 concludes with policy implications and directions for future research.

## 2. Literature Review

### 2.1. Corporate Digital Transformation

Corporate digital transformation represents a fundamental shift in organizational operations, capable of reshaping management practices, enhancing operational efficiency, innovating business models, and optimizing supply chain governance [12]. Through the integration of big data analytics and cross-functional collaboration, digitalization facilitates the alignment of strategic objectives and curtails resource waste attributable to organizational inefficiencies, while simultaneously bolstering decision-making quality and operational agility [13]. Leveraging technologies such as artificial intelligence and cloud computing, digital transformation enables automation and intelligent control of production processes, real-time monitoring and precise regulation of manufacturing operations, and significant reductions in production cycles and material waste [5]. The transformative potential of digitalization extends beyond operational improvements to encompass fundamental changes in how firms create, deliver, and capture value.

The evolution of digital transformation can be conceptualized as progressing through multiple stages: from initial digitization of analog information, to digitalization of business processes, and ultimately to comprehensive digital transformation that fundamentally alters value creation. In the context of Chinese enterprises, this progression has been significantly accelerated by supportive government policies, including the "Internet Plus" strategy and the "New Infrastructure" initiative, as well as the rapid development of digital infrastructure. The integration of digital technologies allows firms to transcend traditional organizational boundaries, fostering ecosystem-level collaboration and enabling more responsive supply chain networks. Recent empirical evidence suggests that the pace and depth of digital transformation vary substantially across industries and firm sizes, with technology-intensive sectors and larger firms generally leading the adoption curve.

The impact of corporate digitalization on organizational management can be analyzed from two perspectives. From the cost and risk perspective, the rapid pace of technological iteration means that substantial capital investments may quickly become obsolete, exposing firms to competitive disadvantages. Empirical evidence suggests that digital transformation elevates technology investment costs, talent acquisition expenses, and data management outlays, thereby potentially diminishing corporate cash flow [14], increasing stock price crash risk [8], and precipitating internal management disruptions. The organizational inertia and resistance to change often encountered during digital transformation can further exacerbate these risks, leading to implementation failures and financial losses. Moreover,

cybersecurity threats and data privacy concerns introduce additional layers of operational risk that firms must navigate during their digital transformation journey.

From the perspective of returns and externalities, digital transformation may harness big data, artificial intelligence, and the Internet of Things to optimize production workflows, achieve automated and intelligent manufacturing, and enhance overall productivity. Digitalization enables the collection, integration, and analysis of massive datasets, furnishing management with more comprehensive and accurate information for demand forecasting and inventory optimization. Furthermore, digital transformation attracts external investor attention, broadens funding channels, and strengthens analyst scrutiny, thereby reinforcing external oversight and improving corporate governance structures [15]. The enhanced transparency facilitated by digital reporting systems also mitigates information asymmetry between insiders and external stakeholders, fostering a more robust investment environment and potentially lowering the cost of capital.

## 2.2. Corporate Carbon Emissions

Regarding the determinants of corporate carbon emissions, the extant literature has primarily focused on two dimensions: internal governance and the external environment. In terms of internal governance, advances in production technology and energy-saving innovations have been shown to significantly attenuate carbon emission intensity [16]. Corporate management mechanisms, including supply chain coordination and strategic decision-making, also exert meaningful influence on emission levels. Effective corporate governance structures, characterized by independent boards and strong executive incentives tied to environmental performance, have been associated with more proactive carbon management strategies. Furthermore, the adoption of environmental management systems (EMS) and the integration of sustainability criteria into corporate performance evaluation have proven instrumental in driving emission reductions at the firm level.

From the external macro-policy perspective, green credit policies achieve emission reductions by improving total factor productivity, while low-carbon pilot programs and carbon emission trading schemes have been demonstrated to significantly curb emissions in pilot cities. The stringency of environmental regulations and the enforcement of emission standards play a pivotal role in shaping corporate environmental behavior. Additionally, stakeholder pressure, including demands from institutional investors, consumers, and non-governmental organizations, increasingly compels firms to disclose their carbon footprints and commit to ambitious reduction targets. The growing prominence of Environmental, Social, and Governance (ESG) frameworks in investment decision-making further amplifies the incentives for firms to manage their carbon emissions proactively.

Despite the abundance of research on carbon emission mitigation strategies, the specific role of corporate digital transformation as a driver of emission reduction remains underexplored. A limited number of studies have begun to examine the intersection of digitalization and environmental performance, but these investigations have largely remained at the macro or industry level, lacking the granularity needed to inform firm-level decision-making. The present study addresses this gap by providing micro-level empirical

evidence on how digital transformation influences carbon emission intensity, thereby contributing to a more nuanced understanding of the pathways through which firms can leverage technology for environmental sustainability.

## 3. Research Hypotheses and Empirical Design

### 3.1. Research Hypotheses

As a transformative organizational strategy, digital transformation can effectively improve firm performance, strengthen risk-bearing capacity, and optimize production efficiency. Internally, digitalization promotes green technological innovation, enhances resource allocation, refines human capital structures, and facilitates specialized division of labor, all of which contribute to reducing carbon emission intensity. In manufacturing contexts, digital transformation enables real-time monitoring and precise optimization of energy consumption throughout the production process, thereby curbing emissions. The deployment of smart sensors and IoT devices allows for granular tracking of energy usage across different production stages, enabling managers to identify inefficiencies and implement targeted interventions. Digital twin technology further enables firms to simulate and optimize production processes virtually before physical implementation, reducing trial-and-error waste.

Furthermore, digital transformation facilitates the transition toward circular economy models by optimizing resource utilization and minimizing waste generation. Advanced analytics can predict equipment maintenance needs, reducing downtime and the associated energy waste. Digital platforms also enable more efficient logistics and supply chain management, optimizing transportation routes and reducing scope 3 emissions. By fostering a culture of data-driven decision-making, digitalization empowers organizations to systematically integrate environmental considerations into their operational strategies. The cumulative effect of these micro-level improvements can yield substantial aggregate reductions in corporate carbon emission intensity. Accordingly, we propose:

**H1:** Corporate digital transformation mitigates corporate carbon emission intensity.

Digital transformation broadens the channels through which firms access scientific research resources, leveraging big data and artificial intelligence to identify potential collaborative opportunities. It simultaneously enhances the efficiency of internal R&D management, thereby incentivizing increased research expenditure and facilitating industrial upgrading. The digitalization of R&D processes, such as the use of digital twins and computer-aided engineering, significantly reduces the time and cost associated with prototyping and testing, thereby increasing the overall return on R&D investments. This enhanced efficiency encourages firms to allocate greater financial resources toward innovation activities, creating a virtuous cycle of technological advancement.

Since carbon emission intensity is fundamentally determined by production efficiency—which in turn depends on the sophistication of production facilities and processes—R&D investment serves as a critical conduit through which digitalization influences emissions. By augmenting R&D spending, firms develop and deploy more advanced energy-saving and emission-reduction technologies, thereby

lowering carbon emission intensity. Increased R&D investment facilitates the discovery of novel materials, the optimization of chemical processes, and the development of renewable energy integration solutions. Consequently, the technological advancements spurred by digitalization-induced R&D investments directly translate into improved environmental performance. The mediating role of R&D investment thus represents a key mechanism through which digital transformation achieves its carbon reduction potential. Accordingly, we propose:

**H2:** Corporate digital transformation positively stimulates internal R&D investment, thereby mitigating carbon emission intensity.

### 3.2. Empirical Design

**Data Sources.** This study employs annual panel data from A-share listed companies over the period 2010–2022. The initial sample is processed as follows: (1) exclusion of ST and PT designated firms, as their abnormal financial status may distort the empirical results; (2) exclusion of financial industry firms, given their unique accounting standards and fundamentally different operational models; (3) exclusion of observations with missing key variables to ensure a balanced and robust dataset; and (4) winsorization of all continuous variables at the 1st and 99th percentiles to mitigate the influence of extreme outliers. All corporate financial data are sourced from the China Stock Market & Accounting Research (CSMAR) database, a widely recognized and reliable repository for Chinese corporate data. The final sample comprises 21,211 firm-year observations spanning 13 years, providing sufficient statistical power for the empirical analysis.

**Model Specification.** To examine the effect of corporate digital transformation on carbon emission intensity, the following baseline regression model is specified:

$$CEI_{it} = \beta_0 + \beta_1 DT_{it} + \beta_2 Controls + \Sigma Industry + \Sigma Year + \varepsilon_{it} \quad (1)$$

where  $i$  indexes the firm and  $t$  the year. CEI denotes corporate carbon emission intensity; DT measures the degree of corporate digital transformation; Controls represents a vector of control variables; Industry and Year capture industry and year fixed effects, respectively, to control for unobservable time-invariant industry characteristics and macroeconomic shocks common to all firms in a given year; and  $\varepsilon$  is the random error term. The coefficient  $\beta_1$  is of primary interest: a significantly negative  $\beta_1$  would support H1, indicating that digital transformation reduces carbon emission intensity.

**Variable Definitions.** (1) Dependent Variable: Carbon

Emission Intensity (CEI). Following established methodologies [17], this study measures carbon emission intensity as the ratio of listed company carbon emissions to operating income (scaled by 10,000). This relative measure accounts for differences in firm scale and production volume, providing a more accurate reflection of carbon efficiency across firms of varying sizes. (2) Independent Variable: Corporate Digital Transformation (DT). Drawing on Wu et al. [18], the degree of digital transformation is quantified by identifying keywords related to digitalization in corporate annual reports, computing their frequency, adding one, and taking the natural logarithm [19]. This text-mining approach captures the strategic emphasis placed on digitalization by corporate management and has been widely validated in the literature. (3) Control Variables: To enhance model accuracy and mitigate omitted variable bias, the following controls are included: firm age (Age), board size (Boardsize), proportion of independent directors (DIR), capital intensity (CI), debt-to-asset ratio (DAR), operating cash flow (OCF), return on assets (ROA), firm size (Size), and the shareholding ratio of the largest shareholder (Top1). Detailed variable definitions are presented in Table 1.

**Table 1.** Variable Definitions and Descriptions

Variable	Name	Description
CEI	Carbon Emission Intensity	Carbon emissions / (Operating income / 10000)
DT	Digital Transformation	Ln(frequency of digital keywords in annual reports + 1)
Age	Firm Age	Ln(years since listing + 1)
Boardsize	Board Size	Ln(number of board members)
DIR	Independent Director Ratio	Proportion of independent directors
CI	Capital Intensity	Total assets / Operating income
DAR	Debt-to-Asset Ratio	Total liabilities / Total assets
OCF	Operating Cash Flow	Net cash flow from operating activities
ROA	Return on Assets	Net income / Average total assets
Size	Firm Size	Ln(total assets)
Top1	Largest Shareholder	Shareholding ratio of the largest shareholder

**Table 2.** Descriptive Statistics

Variable	N	Mean	Std. Dev.	Min	Max
CEI	21,211	0.462	0.573	0.0422	2.318
DT	21,211	1.225	1.254	0	4.625
Age	21,211	2.101	0.777	0.693	3.332
Boardsize	21,211	8.464	1.602	5	14
DIR	21,211	37.60	5.302	33.33	57.14
CI	21,211	2.194	1.391	0.470	8.848
DAR	21,211	0.406	0.192	0.0569	0.874
OCF	21,211	6.716e+08	2.009e+09	-1.077e+09	1.520e+10
ROA	21,211	0.0520	0.0660	-0.222	0.239
Size	21,211	22.17	1.218	20.06	25.93
Top1	21,211	33.82	14.04	9.560	71.74

**Descriptive Statistics.** Table 2 presents the descriptive statistics for the principal variables. The mean carbon

emission intensity (CEI) is 0.462, suggesting a relatively moderate overall emission level among Chinese listed firms, though substantial cross-sectional variation exists, as evidenced by the standard deviation of 0.573 and the range from 0.0422 to 2.318. This wide dispersion reflects the heterogeneous nature of China's industrial landscape, encompassing both heavy-emission manufacturing firms and low-emission service-oriented enterprises. The mean digital transformation index (DT) is 1.225, indicating that the overall level of digitalization remains comparatively low, with considerable heterogeneity across firms—notably, the minimum value of zero implies that some enterprises have yet to initiate digital transformation, while the maximum value of 4.625 highlights the presence of highly digitalized industry leaders. The control variables all fall within reasonable ranges, consistent with prior studies on Chinese listed companies.

## 4. Empirical Results and Analysis

### 4.1. Baseline Regression Results

Table 3 reports the baseline regression results examining the impact of corporate digital transformation on carbon emission intensity. Column (1) presents the ordinary least squares (OLS) estimates without any fixed effects, yielding a coefficient of -0.122 for DT, which is statistically significant at the 1% level. This initial finding indicates that greater digital transformation is strongly associated with lower carbon emission intensity. To rigorously account for unobservable confounding factors, columns (2) through (4)

progressively incorporate fixed effects. Column (2) includes year fixed effects, resulting in a DT coefficient of -0.128, significant at the 1% level. Column (3) introduces industry fixed effects, yielding a DT coefficient of -0.005, also significant at the 1% level. Finally, column (4) presents the most stringent specification, incorporating both industry and year fixed effects simultaneously. The coefficient of DT remains significantly negative at -0.008 (t-statistic = -6.314), significant at the 1% level.

These consistent results across all four specifications provide robust support for H1, confirming that corporate digital transformation effectively attenuates carbon emission intensity. The substantial reduction in the magnitude of the DT coefficient from column (1) to columns (3)-(4) suggests that a significant portion of the raw correlation between digitalization and carbon emissions is attributable to industry-specific characteristics, underscoring the importance of controlling for industry fixed effects. The control variables also exhibit expected signs and significance levels. Firm size (Size) is positively associated with carbon emission intensity, suggesting that larger firms tend to have higher relative emissions. Return on assets (ROA) is consistently negative and highly significant, indicating that more profitable firms are generally more efficient in their carbon management. Capital intensity (CI) shows a significantly negative relationship with carbon emission intensity, implying that firms with higher capital intensity may have invested in more modern, energy-efficient equipment.

Table 3. Baseline Regression Results

Variable	(1) CEI	(2) CEI	(3) CEI	(4) CEI
DT	-0.122*** (-20.870)	-0.128*** (-20.664)	-0.005*** (-3.796)	-0.008*** (-6.314)
Age	0.043*** (3.274)	0.043*** (3.175)	0.011*** (4.433)	0.011*** (4.429)
Boardsize	0.002 (0.240)	0.005 (0.607)	-0.002 (-1.560)	-0.001 (-0.477)
DIR	-0.003 (-1.277)	-0.002 (-1.193)	-0.000 (-1.191)	-0.000 (-1.057)
CI	-0.042*** (-6.207)	-0.041*** (-6.030)	-0.020*** (-8.789)	-0.018*** (-8.190)
DAR	0.072 (1.224)	0.081 (1.370)	0.021* (1.830)	0.024** (2.144)
OCF	0.000*** (2.969)	0.000*** (2.775)	-0.000*** (-3.628)	-0.000*** (-4.192)
ROA	-0.571*** (-4.598)	-0.558*** (-4.433)	-0.593*** (-17.653)	-0.577*** (-17.128)
Size	0.054*** (4.548)	0.051*** (4.174)	0.009*** (4.452)	0.009*** (4.088)
Top1	0.002** (2.210)	0.002** (2.492)	0.000*** (2.853)	0.001*** (3.551)
Constant	-0.572** (-2.191)	-0.510* (-1.950)	-0.009 (-0.206)	-0.291 (-0.988)
N	21,211	21,211	21,211	21,211
R <sup>2</sup>	0.128	0.135	0.934	0.937
Industry FE	No	No	Yes	Yes
Year FE	No	Yes	No	Yes

### 4.2. Robustness Tests

To ensure the reliability of the baseline findings and address potential methodological concerns, this study conducts two rigorous robustness checks. First, propensity score matching (PSM) is employed to address potential systematic differences between digitally transformed and

non-transformed firms. The decision to undergo digital transformation is not entirely random; firms with better financial health or specific industry characteristics may be more likely to adopt digital technologies, introducing selection bias into the estimates. Following Pan and Han [20], a one-to-one nearest neighbor matching approach is performed using firm size, profitability, and other covariates

to construct a comparable control group. This procedure yields 14,444 matched observations. As shown in columns (1) and (2) of Table 4, the coefficient of DT remains significantly negative at the 1% level in both specifications, confirming that the baseline results are not driven by observable sample selection bias.

Second, given that the dependent variable (carbon emission intensity) is strictly non-negative and may exhibit truncation characteristics inconsistent with standard OLS assumptions, a Tobit model is estimated as an alternative specification. The

Tobit model is particularly well-suited for dependent variables that are censored or bounded at zero, as it accounts for the probability mass at the lower bound. Columns (3) and (4) of Table 4 demonstrate the results of the Tobit regressions. The DT coefficient remains significantly negative at the 1% level under this alternative econometric specification, further corroborating the robust conclusion that digital transformation effectively mitigates carbon emission intensity regardless of the estimation method employed.

**Table 4. Robustness Tests**

Variable	(1) PSM	(2) PSM	(3) Tobit	(4) Tobit
DT	-0.121*** (-19.933)	-0.007*** (-4.982)	-0.121*** (-19.940)	-0.007*** (-5.014)
Age	0.045*** (3.542)	0.008*** (3.339)	0.045*** (3.544)	0.008*** (3.361)
Boardsize	0.000 (0.059)	0.000 (0.240)	0.000 (0.059)	0.000 (0.241)
DIR	-0.002 (-1.177)	-0.000 (-1.351)	-0.002 (-1.177)	-0.000 (-1.360)
CI	-0.035*** (-5.300)	-0.017*** (-8.643)	-0.035*** (-5.302)	-0.017*** (-8.700)
DAR	0.029 (0.490)	0.014 (1.208)	0.029 (0.491)	0.014 (1.216)
OCF	0.000*** (2.815)	-0.000*** (-3.647)	0.000*** (2.816)	-0.000*** (-3.671)
ROA	-0.532*** (-4.177)	-0.517*** (-15.323)	-0.532*** (-4.179)	-0.517*** (-15.422)
Size	0.050*** (4.348)	0.008*** (3.926)	0.050*** (4.350)	0.008*** (3.951)
Top1	0.002** (2.068)	0.000*** (3.068)	0.002** (2.069)	0.000*** (3.088)
Constant	-0.492* (-1.942)	-0.296 (-0.723)	-0.492* (-1.943)	-0.296 (-0.728)
N	14,444	14,444	14,444	14,444
R <sup>2</sup>	0.133	0.938	0.1960	0.479
Industry FE	No	Yes	No	Yes
Year FE	No	Yes	No	Yes

### 4.3. Endogeneity Tests

**Table 5. Heckman Two-Stage Method**

Variable	(1) DT	(2) CEI
DT		-0.009*** (-6.506)
IMR		-0.119*** (-4.726)
Age	-0.019 (-1.366)	0.013*** (4.695)
Boardsize	0.005 (0.788)	-0.002 (-1.253)
DIR	0.007*** (3.273)	-0.001 (-1.324)
CI	-0.040*** (-6.326)	-0.015*** (-6.062)
DAR	-0.219*** (-3.648)	0.049*** (4.004)
OCF	-0.000*** (-2.941)	-0.000*** (-3.286)
ROA	-0.135 (-0.845)	-0.635*** (-17.866)
Size	0.189*** (16.202)	-0.004* (-1.651)
Top1	-0.001 (-1.217)	0.000*** (3.340)
Constant	-11.458 (-0.004)	1.014*** (3.994)
N	25,359	25,129
R <sup>2</sup>	0.2187	0.933
FE	Yes	Yes

The assignment of firms to the treated group (i.e., those with higher digital transformation) is not random but driven

by unobservable factors that may correlate with both the explanatory variable and the error term, giving rise to endogeneity concerns. Furthermore, there may exist reverse causality, where firms with high carbon emission intensity are compelled by regulatory pressure to accelerate their digital transformation. This study addresses these endogeneity issues through two distinct approaches: the Heckman two-stage method and the instrumental variable approach.

**Heckman Two-Stage Method.** To account for potential sample selection bias, the Heckman two-stage procedure is employed [21]. In the first stage, a Probit model is used to estimate the probability of a firm undergoing digital transformation, utilizing the explanatory and control variables along with fixed effects. The inverse Mills ratio (IMR) derived from this first-stage estimation is then incorporated into the second-stage regression as an additional control variable to correct for selection bias. As reported in Table 5, column (2), the coefficient of the IMR is -0.119 and significant at the 1% level, indicating that selection bias was indeed present in the original specification. Crucially, the coefficient of DT remains negative (-0.009) and significant at the 1% level after controlling for the IMR, confirming that the

baseline conclusion is robust to selection bias.

**Instrumental Variable Approach.** To further address endogeneity arising from omitted variables or reverse causality, this study employs industry-level and province-level averages of digital transformation as instrumental variables. These instruments are theoretically valid because the average digitalization level of an industry or province reflects the broader technological environment and peer pressure, which directly influences a firm's digitalization decisions (relevance condition), but does not directly affect the individual firm's carbon emission intensity except through the firm's own digital transformation (exogeneity condition). Table 6 presents the two-stage least squares (2SLS) results. In the first-stage regressions, both the industry average (column 1) and province average (column 3) exhibit significantly positive coefficients (1.003 and 0.471, respectively, both at the 1% level), confirming their strong relevance as instruments. In the second-stage regressions, the fitted values of DT yield significantly negative coefficients (-0.131 in column 2 and -0.032 in column 4), consistent with the baseline findings and confirming that digital transformation causally reduces carbon emission intensity.

**Table 6.** Instrumental Variable Estimation

Variable	(1) 1st Stage	(2) 2nd Stage	(3) 1st Stage	(4) 2nd Stage
DT_hat		-0.131*** (-11.964)		-0.032** (-2.285)
IV-Industry	1.003*** (20.159)			
IV-Province			0.471*** (8.797)	
Age	-0.023 (-1.221)	0.009*** (3.047)	-0.005 (-0.282)	0.011*** (3.958)
Boardsize	-0.000 (-0.003)	-0.001 (-0.871)	0.003 (0.355)	-0.001 (-0.877)
DIR	0.004 (1.493)	0.000 (1.268)	0.004 (1.515)	0.000 (0.074)
CI	-0.028*** (-3.000)	-0.021*** (-7.986)	-0.022** (-2.298)	-0.018*** (-7.134)
DAR	-0.243*** (-2.992)	0.006 (0.464)	-0.179** (-2.225)	0.027** (2.190)
OCF	-0.000 (-0.732)	-0.000*** (-4.609)	-0.000 (-1.345)	-0.000*** (-4.148)
ROA	-0.452*** (-2.593)	-0.698*** (-18.873)	-0.350** (-2.006)	-0.656*** (-18.289)
Size	0.160*** (10.004)	0.027*** (8.959)	0.155*** (9.639)	0.011*** (3.288)
Top1	-0.002** (-2.163)	0.000 (1.350)	-0.002* (-1.936)	0.000*** (2.822)
Constant	-3.353*** (-6.911)	-0.579*** (-3.633)	-4.366*** (-8.215)	-0.150 (-0.919)
N	25,359	25,129	25,359	25,129
R <sup>2</sup>	0.377	0.934	0.375	0.933
FE	Yes	Yes	Yes	Yes

## 5. Further Analysis

### 5.1. Mechanism Analysis

While the preceding analysis has robustly established the mitigating effect of digital transformation on carbon emission intensity, the underlying transmission mechanism warrants further investigation. Theoretical analysis suggests that digital transformation may reduce emissions by stimulating corporate R&D investment, which in turn facilitates the development and adoption of green technologies and more efficient production processes. This section employs a rigorous three-step mediation test, following the classical Baron and Kenny (1986) approach, to empirically examine

whether R&D investment serves as a mediating channel. The regression models are specified as follows:

$$CEI_{it} = a_0 + a_1DT_{it} + a_2Controls + S_{Industry} + S_{Year} + e_{it} \quad (2)$$

$$RDS_{it} = b_0 + b_1DT_{it} + b_2Controls + S_{Industry} + S_{Year} + e_{it} \quad (3)$$

$$CEI_{it} = c_0 + c_1DT_{it} + c_2RDS_{it} + c_3Controls + S_{Industry} + S_{Year} + e_{it} \quad (4)$$

Table 7 presents the comprehensive mediation test results. In column (1), which corresponds to equation (2), the coefficient of DT is -0.009, significant at the 1% level, confirming the direct negative effect of digitalization on carbon emission intensity. In column (2), which corresponds

to equation (3), the coefficient of DT on R&D investment share (RDS) is 0.380, significant at the 1% level. This robust finding indicates that digital transformation significantly promotes corporate R&D spending, likely by enhancing innovation efficiency, broadening access to technological resources, and reducing the marginal cost of research activities through digital tools.

In column (3), which corresponds to equation (4), both DT and RDS are included in the regression simultaneously. The coefficient of RDS is -0.004, significant at the 1% level, demonstrating that increased R&D investment effectively reduces carbon emission intensity through the development

and deployment of cleaner technologies and more efficient production methods. Notably, the DT coefficient in column (3) (-0.007) remains significant but is smaller in absolute value than the coefficient in column (1) (-0.009), indicating that the inclusion of the mediator absorbs part of the total effect. The significance of both the mediator (RDS) and the independent variable (DT) in the final model confirms the partial mediating role of R&D investment. This empirically validates H2: digital transformation mitigates carbon emission intensity, in part, by stimulating R&D expenditure that leads to green technological innovation.

**Table 7. Mechanism Test: R&D Investment as Mediator**

Variable	(1) CEI	(2) RDS	(3) CEI
DT	-0.009*** (-6.374)	0.380*** (8.216)	-0.007*** (-5.218)
RDS			-0.004*** (-7.518)
Age	0.010*** (4.152)	-0.622*** (-9.059)	0.008*** (3.257)
Boardsize	-0.001 (-1.003)	0.061* (1.862)	-0.001 (-0.826)
DIR	-0.000 (-1.024)	0.018* (1.941)	-0.000 (-0.826)
CI	-0.016*** (-7.229)	0.754*** (13.730)	-0.013*** (-5.554)
DAR	0.035*** (3.023)	-2.698*** (-8.593)	0.024** (2.132)
OCF	-0.000*** (-4.658)	0.000 (1.595)	-0.000*** (-4.522)
ROA	-0.578*** (-16.937)	-3.656*** (-5.262)	-0.592*** (-17.514)
Size	0.009*** (4.073)	-0.137** (-2.285)	0.008*** (3.874)
Top1	0.001*** (3.618)	-0.011*** (-3.349)	0.000*** (3.384)
Constant	-0.084 (-0.368)	-0.854 (-0.624)	-0.088 (-0.384)
N	22,031	22,181	22,031
R <sup>2</sup>	0.935	0.412	0.935
FE	Yes	Yes	Yes

## 5.2. Heterogeneity Analysis

The baseline regression establishes an average effect across the entire sample, but it does not account for potential heterogeneity in the relationship between digital transformation and carbon emissions across different institutional and governance contexts. Firms operate under varying degrees of external scrutiny and possess different ownership structures, which may significantly moderate their environmental behavior and the effectiveness of digital transformation in reducing emissions. This section explores such heterogeneity along two critical dimensions: audit quality and ownership structure.

**Audit Quality Heterogeneity.** Auditors serve as a critical external governance mechanism, and those from Big Four accounting firms (Deloitte, PricewaterhouseCoopers, Ernst & Young, and KPMG) typically provide higher-quality audit services owing to their professional reputation, abundant resources, and rigorous standards [22] [23] [24]. High-quality audits enhance the credibility of financial disclosures and information transparency [25] [26], which may prompt firms to manage carbon emissions more prudently to avoid reputational damage and regulatory scrutiny. When auditors are not from the Big Four, the verification of carbon disclosure accuracy may be less thorough [27] [28], potentially weakening the market's response to improved

carbon disclosure quality and reducing the incentive for firms to invest in emission reduction through digital means.

Following established measurement approaches [29] [30], this study classifies firms based on whether they engage Big Four auditors. Table 8 reports the results: in the non-Big Four subsample (column 1, N=1,309), the DT coefficient is -0.020 but statistically insignificant; in the Big Four subsample (column 2, N=23,820), the DT coefficient is -0.009, significant at the 1% level. This confirms that the mitigating effect of digital transformation on carbon emission intensity is more pronounced among firms with higher audit quality, highlighting the complementary role of external oversight in amplifying the environmental benefits of digitalization.

**Ownership Structure Heterogeneity.** State-owned enterprises (SOEs) occupy a distinctive position in China's economic system, characterized by unique property rights and governance structures [31] [32]. SOEs typically bear greater social responsibilities and face stronger policy constraints and public scrutiny regarding carbon emission management [33], making them more inclined to actively deploy digital technologies for energy conservation and emission reduction. The political accountability of SOE managers to government objectives, including environmental targets, creates additional incentives for proactive carbon management. Non-state-owned enterprises, by contrast, may prioritize short-term economic returns, with relatively weaker motivation for

carbon management unless driven by direct financial incentives or market pressure.

**Table 8.** Heterogeneity Test: Audit Quality

Variable	(1) Non-Big Four	(2) Big Four
DT	-0.020 (-1.454)	-0.009*** (-6.901)
Age	0.000 (0.013)	0.014*** (4.710)
Boardsize	-0.001 (-0.172)	-0.002 (-1.531)
DIR	0.000 (0.233)	-0.000 (-0.705)
CI	-0.027** (-2.093)	-0.016*** (-6.423)
DAR	0.141* (1.822)	0.030** (2.545)
OCF	-0.000 (-0.500)	-0.000*** (-5.152)
ROA	-0.745*** (-4.456)	-0.609*** (-16.974)
Size	0.010 (0.812)	0.009*** (3.537)
Top1	0.000 (0.477)	0.000*** (3.384)
Constant	1.002*** (3.448)	-0.079 (-0.521)
N	1,309	23,820
R <sup>2</sup>	0.925	0.935
FE	Yes	Yes

Following established classification methods [34], this study divides the sample by ownership type. Table 9 presents the results: the DT coefficient is -0.007 (significant at 5%) for non-SOEs (N=8,096) and -0.009 (significant at 1%) for SOEs (N=15,286). The larger absolute coefficient and higher

significance level for SOEs confirm that the mitigating effect of digital transformation on carbon emission intensity is more salient among state-owned enterprises, reflecting their dual role as economic actors and policy implementers in China's environmental governance framework.

**Table 9.** Heterogeneity Test: Ownership Structure

Variable	(1) Non-SOE	(2) SOE
DT	-0.007** (-2.478)	-0.009*** (-5.517)
Age	0.015** (2.268)	0.009** (2.433)
Boardsize	0.000 (0.055)	-0.003 (-1.624)
DIR	0.000 (0.306)	-0.001* (-1.755)
CI	-0.026*** (-4.938)	-0.011*** (-3.602)
DAR	-0.014 (-0.656)	0.052*** (3.537)
OCF	-0.000*** (-3.863)	-0.000*** (-3.157)
ROA	-0.967*** (-12.962)	-0.481*** (-11.789)
Size	0.010*** (2.612)	0.005 (1.588)
Top1	0.000 (0.991)	0.000** (2.226)
Constant	0.320** (2.300)	-0.099 (-0.433)
N	8,096	15,286
R <sup>2</sup>	0.940	0.929
FE	Yes	Yes

## 6. Conclusion

Against the backdrop of the rapidly evolving digital economy and the imperative of achieving dual carbon targets, this study investigates the impact and underlying mechanism of corporate digital transformation on carbon emission intensity using panel data from China's A-share listed companies over 2010-2022. The empirical findings yield

several key conclusions that advance both theoretical understanding and practical application in this domain.

First, corporate digital transformation significantly attenuates carbon emission intensity, a result that withstands multiple robustness checks including propensity score matching, Tobit regression, the Heckman two-stage correction, and instrumental variable estimation. The consistency of this finding across diverse econometric

specifications provides compelling evidence that the relationship is not an artifact of methodological choices or sample characteristics, but rather reflects a genuine causal mechanism whereby digitalization drives emission reductions at the firm level.

Second, the mechanism analysis demonstrates that digital transformation reduces carbon emission intensity primarily by stimulating corporate R&D investment, which in turn facilitates green technological innovation and production process optimization. The partial mediation effect of R&D investment suggests that while innovation is a critical pathway, other channels—such as improved resource allocation efficiency and enhanced supply chain management—may also contribute to the overall emission reduction effect. This finding underscores the importance of viewing digital transformation not merely as a technological upgrade, but as a comprehensive organizational strategy that catalyzes innovation-driven sustainability.

Third, heterogeneity analysis reveals that the mitigating effect is more pronounced among state-owned enterprises and firms audited by Big Four accounting firms, underscoring the moderating roles of ownership structure and external governance quality. The stronger effect among SOEs reflects the unique institutional incentives and policy accountability that characterize state ownership in China, while the audit quality finding highlights the complementary role of external monitoring in ensuring that digitalization translates into tangible environmental improvements.

These findings carry important policy implications at multiple levels. For corporate practitioners, the results suggest that digital transformation should be strategically integrated with sustainability objectives, with particular emphasis on channeling digitalization-driven efficiencies toward R&D investment in green technologies. Firms should actively embrace digital tools not merely for operational efficiency, but as a core component of their environmental strategy. Investment in digital infrastructure should be accompanied by corresponding investments in human capital development to ensure that employees can effectively leverage new technologies for environmental management.

For policymakers, the findings highlight the importance of strengthening external oversight mechanisms—particularly audit quality and the scrutiny of corporate carbon disclosure—to amplify the emission-reduction benefits of digitalization. Furthermore, given the more pronounced effects observed among SOEs, targeted policy support for digital transformation in the private sector may help broaden the reach of emission reduction efforts. Governments should consider providing subsidies, tax incentives, or preferential financing to alleviate the financial burden of digital transformation for non-state-owned enterprises, thereby democratizing access to the environmental benefits of digitalization.

This study is not without limitations, which also point to promising directions for future research. First, the measurement of digital transformation based on annual report keyword frequency, while widely adopted, may not fully capture the depth and breadth of a firm's digitalization efforts. Future studies could employ more granular measures, such as IT investment data or digital patent counts, to provide a more comprehensive assessment. Second, the analysis focuses on the aggregate effect of digital transformation without distinguishing between specific types of digital technologies (e.g., AI, IoT, blockchain). Investigating which technologies

are most effective in driving carbon reductions would yield more targeted policy recommendations. Third, the sample is limited to Chinese listed companies, and the generalizability of the findings to other institutional contexts warrants further examination. Cross-country comparative studies could shed light on how different regulatory environments and economic structures moderate the digitalization-emission relationship.

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