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# Digital technology, green innovation, and the carbon performance of manufacturing enterprises

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With the continuous promotion of digitalization and the global trend toward a low-carbon economy, the issue of whether enterprises can enhance their carbon performance with the assistance of digital technology has aroused widespread attention from both academia and industry. In order to explore whether digital technology can improve the carbon performance of manufacturing enterprises, this study, based on resource orchestration theory and signaling theory, utilizes data from China's A-share manufacturing enterprises from 2012 to 2021 to empirically investigate the relationship between digital technology and the carbon performance of manufacturing firms. It also explores the mediating conduction path and boundary influencing factors between them. Its findings demonstrate that: digital technology is capable of improving carbon performance; green innovation (including green technology and green collaboration) has partially mediating effects; there is a catalytic role for environmental information disclosure in utilizing digital technology to enhance carbon performance. Building on this, we find that the impacts of digital technology, green innovation, and environmental information disclosure on carbon performance vary due to differences in the nature of industries and the strategic aggressiveness of enterprises. Specifically, the role of digital technology on carbon performance seems somewhat more pronounced among firms in the high-tech industry and those employing defensive and analytical strategies. Additionally, the effects generated by green innovation and environmental information are more pronounced in the high-tech industry and among enterprises that adopt analytical strategies. This study reveals the inherent mechanism of digital technology in enhancing the carbon performance of manufacturing enterprises, which provides empirical evidence for the development of digital technology and the improvement of carbon performance in manufacturing enterprises, thus helping promote low-carbon economic transformation.

## KEYWORDS

carbon performance, digital technology, green innovation, green collaborative innovation, green technology innovation, environmental information disclosure

## 1 Introduction

Since the Industrial Revolution, excessive production and consumption have led to the serious depletion and destruction of resources along with a rapid increase in carbon emissions. This escalation has intensified the global climate crisis. Consequently, reducing carbon emissions and promoting sustainable development have become prominent topics of global discussion (Dogan et al., 2022). The concept of a “low-carbon economy” (Samargandi and Sohag, 2022), which emphasizes both environmental protection and economic growth, has gradually emerged and garnered significant attention. Scholars from various countries have thus studied the issue of carbon emissions from various perspectives. For example, they have explored industry sectors such as transportation and power, where, for example, technological advancements have facilitated energy substitution in the transportation sector of Bangladesh, leading to a reduction in carbon emissions (Raza, 2023). Liu H. et al. (2024) observed that energy structure and consumption affect carbon dioxide emissions in the power industry, and that carbon reduction technology plays a significant inhibitory role. From a macro perspective, scholars have identified the optimization of energy regeneration (Xiao et al., 2024), implementing green technology (Ren et al., 2024), promoting renewable energy policies (Jiang and Raza, 2023), increasing energy intensity (Raza and Li, 2023), and improving the energy structure as crucial measures to reduce regional carbon emissions. Energy-efficient technologies, in turn, are crucial to increasing energy intensity (Jiang and Raza, 2022). Additionally, capital flows play a significant role globally (Ma, 2023). For instance, Raza pointed out that capital growth can lower carbon emissions, reduce energy waste, and contribute to energy technology advancement, thus helping to control carbon emissions (Raza and Tang, 2022). Wang highlighted that the level of green finance (Wang et al., 2024), financial technology (Chen W. J. et al., 2024), and economic development (Ji et al., 2024) all contribute to reducing regional carbon emissions and ensuring sustainable development. However, some scholars have also pointed out that foreign investment has a negative impact on curbing carbon emissions (Ma and Zhu, 2024).

The manufacturing sector, as a fundamental industry for economic construction and development, thus plays a crucial role in global economic growth. However, the crude development paradigm of “high input, high emission, and high consumption” in the manufacturing has made it the primary source of carbon emissions. As indicated by statistics, carbon emissions from the manufacturing sector, including energy consumption and direct emissions from production processes, account for about 30% of global carbon emissions. This makes it a significant contributor to global carbon emissions. Therefore, promoting carbon emission reduction in the manufacturing sector is crucial for addressing global climate issues. In addition, as one of the world’s largest carbon emitters and the world’s largest manufacturing country, China not only contributes to the stabilization of the global economy but also affects the quality of global ecological environment. Therefore, promoting the green and low-carbon transformation of China’s manufacturing industry is a key goal in achieving “carbon peak” and “carbon neutrality,” thereby contributing to global carbon reduction efforts.

However, exploring how to effectively promote green development and foster the symbiosis of environmental and economic benefits for manufacturing enterprises from a micro perspective is a crucial issue that requires attention from both academia and industry. In addition, since carbon performance directly determines overall carbon emission levels (Gao et al., 2021), it can reflect not only information about an enterprise’s emission reductions but also the economic inflow generated by carbon emissions during the operation of the enterprise (Wang M. L. et al., 2023). Therefore, it is of great theoretical and practical significance to find effective ways to improve the carbon performance of manufacturing enterprises and assist them to develop sustainably. This will help promote the realization of China’s “double carbon” goal and further alleviate the global carbon emission problem while ensuring the stable development of the social economy.

In the meantime, the emergence of digital technology, exemplified by cloud computing and big data, has created opportunities for manufacturing enterprises to undergo low-carbon transformation. However, existing research reveals no unified conclusion from industry and academia regarding the linkage between carbon performance and digital technology. According to the Global E-Sustainability Promotion Institute (GESI), digital technology has the hidden ability to decouple carbon emissions from economic growth, thereby driving improvements in corporate carbon performance. Some argue that enterprises can leverage big data, blockchain, and other digital technologies to integrate innovations into energy-saving and emission-reduction processes, ultimately enhancing the reduction of corporate emissions (Chen Q. L. et al., 2024; Liu Y. J. et al., 2024). Some have argued that advances in digital technology result, to a certain extent, in the additional consumption of resources, leading to increased greenhouse gas emissions (Lange et al., 2020). The construction of digital industry facilities can lead to high energy consumption (Bianchini et al., 2023), thus resulting in increased carbon emissions (Lange et al., 2020). Some studies also find the presence of a non-linear relationship, initially suppressed and then revealed (Zheng et al., 2023; Zhan and Pu, 2024).

Others have investigated the mechanisms through which digital technology impacts carbon emissions, among which are industrial structure (Zeng and Yang, 2023) and improvements in energy efficiency and green technology innovation capacity (Liu H. et al., 2024). Most research affirms the ability of green innovation to solve corporate environmental problems (Hojnik and Ruzzier, 2016b; Song and Yu, 2018; Dong et al., 2023), indicating that it can indirectly contribute to carbon performance by improving economic efficiency through the optimization of factors such as allocation (Deng et al., 2019) and cost reduction (Peng et al., 2020). However, others have pointed out that the rebound effect of green innovation can lead to an increase in net carbon emissions (Li et al., 2020) due to factors such as the potential hindrance of cost pressure during the investment process (Habiba et al., 2022). In addition, the existing literature mainly focuses on independent innovation. As collaborative innovation becomes increasingly important for enterprise innovation, the academic community has proposed the concept of green collaborative innovation, which indicates that it can integrate multi-disciplinary perspectives and resources to help solve environmental problems, leading to a new green innovation

method that balances economic growth and environmental sustainability. Therefore, this paper considers the autonomy and collaborative behaviors of green innovation (Lian et al., 2023). However, some scholars have pointed out that the green market environment, synergistic capacity and benefits, and synergistic costs and risks will affect the enthusiasm and innovation stability of green collaborative innovation (Yang and Zou, 2023), thus affecting its effect. Taken together, this paper selects green innovation as a mediating variable, specifically as green technology innovation and green collaborative innovation, to explore whether both autonomous and collaborative green innovation play a role in the relationship between digital technology and carbon performance.

This paper proposes that when analyzing how digital technology affects carbon performance, the boundary environment of enterprises must be considered. Based on signaling theory, enterprises are non-independent individuals in the market environment, and their strategic behaviors will be affected by internal and external influences. Environmental disclosure is the primary means of corporate communication regarding the environmental status to external stakeholders (Zhang C. et al., 2024), influences corporate risk (Lee et al., 2024), investments (Pan et al., 2023), share prices (Yang et al., 2023), and the selection of green innovation strategies (Lu and Li, 2023). These factors, in turn, impact the allocation of resources aimed at improving carbon performance. Therefore, this paper chooses the factor of environmental information disclosure to explore its digital technology and carbon performance moderating role. Based on the literature study, the following questions are therefore worth considering.

**Question 1:** What is the correlation between firms' carbon performance and digital technology?

**Question 2:** Can green innovation serve as a mediating mechanism between digital technology and firms' carbon performance? Are the environmental impacts of green technology innovation and green collaborative innovation the same?

**Question 3:** Does environmental information disclosure play a moderating role between digital technology and firms' carbon performance?

To address these issues, this paper will first empirically analyze these questions based on resource orchestration and signaling theory. Second, it will utilize data from China's A-share listed manufacturing enterprises from 2012 to 2021, and, to ensure its quality and reliability, this paper will employ a fixed-effects model for linear regression on the panel data and use an instrumental variable approach in the robustness test to address endogeneity. It will further explore and test the mechanism paths and boundary-influencing factors between the two, as well as analyze heterogeneity according to the nature of the industries in which the firms are situated and the different strategic aggressiveness.

The following contributions are made by this research. 1) This paper focuses on China's manufacturing enterprises, exploring the effect of digital technology on carbon performance through micro-level research. 2) Previous studies have mainly focused on autonomous green innovation, but this paper considers the increasingly important function of collaborative innovation in today's enterprises, dividing green innovation into two categories:

green technology innovation and green collaborative innovation. It explores their roles in the process of digital technology affecting carbon performance from the perspectives of autonomous and collaborative behavior, thus expanding research on the path mechanism of carbon performance. 3) This study identifies the mechanism of the moderating impact of environmental information disclosure, enriching research on the boundary factors of digital technology that affect carbon performance. 4) Most heterogeneity studies focus on regions and the nature of enterprise property rights. In its further analysis, this paper identifies that the heterogeneity of the study exists across samples with different industry natures and varying degrees of strategic aggressiveness. This provides a basis for differentiated promotion of the "dual carbon" goal in China's manufacturing industry.

## 2 Literature review and research hypotheses

### 2.1 The impact of digital technology on corporate carbon performance

Digital technology offers new opportunities for enhancing the carbon performance of enterprises. Borrowing from the theory of resource orchestration, digital technology at the enterprise level can effectively utilize vast data resources. It uses data as the basic element to optimize production and manufacturing (Xie et al., 2024) so that it can strip and reuse the enterprise's idle resources in time and build a more reasonable and better resource combination within the enterprise, thus controlling carbon emissions (Wen et al., 2022). Generally, lower carbon emissions indicate a better carbon performance of an enterprise (Wang S. Y. et al., 2023). From a regional perspective, digital technology can better integrate into the design, manufacturing, and operations of various industries and processes (Weigel and Manfred, 2019; Zhong et al., 2022) than traditional manufacturing enterprises. Digital technology can empower enterprises to optimize the industrial structure while maintaining economic benefits and reduce the mismatch of resources, thus reducing carbon emissions (Stanko and Rindfleisch, 2023). According to signaling theory, in market competition, as the rapid accumulation of data by manufacturing enterprises increases dramatically, digital technology, as a basic and strategic resource for obtaining development information (Song et al., 2019), can significantly improve the search scope, transmission speed, and transparency of information (Yoo et al., 2012). To a certain extent, it enhances the acuity and flexibility of enterprises to perceive green information and technology. Digital technology reduces marginal cost through the sharing of data, which provides the conditions for the enterprises to utilize efficient energy-saving activities in terms of time and space (Hui et al., 2024). As a result, enterprises can indirectly reduce carbon emissions and enhance carbon performance by improving the allocation efficiency of innovation resources to reduce energy consumption and increase inputs. Consequently, we have formulated the following research hypothesis:

**Hypothesis 1:** Digital technology can improve enterprise carbon performance.

## 2.2 The mediating role of green innovation

Driven by the “double carbon” goal, green innovation has become a ready tool for businesses to solve environmental problems (Luo et al., 2023). Green innovation encompasses a range of innovative activities, including technology, products, and management and service-related systems (Hojnik and Ruzzier, 2016a). Research has highlighted the significance of green technology innovation, including process improvement and material research and development, in facilitating enterprises to achieve a mutually beneficial outcome with both environmental and economic advantages. Nikzad and Sedigh (2017) and Xie Xuemei et al. have identified green innovation behaviors that transcend organizational boundaries in their analysis of the green transformation process of enterprises. They have defined this phenomenon as “green collaborative innovation”, wherein multiple entities are able to complement and optimize green technologies and knowledge across various fields (Xie and Han, 2022). Using the research literature, green innovation can be categorized into two types from the perspective of research and development (R&D): *green technology innovation*, representing enterprises’ independent R&D capability and *green collaborative innovation*, representing enterprise R&D cooperation.

Based on resource orchestration theory, the capability to integrate resources can assist enterprises in creating higher value (Zhu and Li, 2023), which also gives them competitive advantage (Matinano et al., 2019). Digital technology can liberate information by assimilating technology, knowledge, and information resources (Yuan and Pan, 2023) for strategic green layout. It can empower the enterprise’s innovation, providing new and efficient technologies for businesses to implement green innovation activities. Green technology innovation is thus enhanced so that enterprises can use the green power of resources by focusing on cleaner production and end-of-pipe technologies. They can realize the substitution of green energy and other methods (Han et al., 2024) to reduce negative consequences for the environment (Zhang et al., 2019) and accelerate the improvement of carbon performance. According to signaling theory, digital technology facilitates the creation of a cooperation network for enterprises, which can help them overcome geographical and resource limitations, expand the scope of green innovation by enhancing information exchange among different enterprises (Tang et al., 2023), and provide internal and external resources for green innovation on a broader spatial and temporal scale (Li et al., 2023). Digital technology also enables the collection of technological knowledge across multiple fields, allowing green innovation to achieve a synergistic innovation effect of “1 + 1 > 2”, improve the overall efficiency of green innovation for enterprises and stakeholders, and indirectly remove barriers to enhancing the carbon performance of enterprises and the industry as a whole. These research hypotheses are therefore proposed:

**Hypothesis 2:** Green innovation plays a mediating role between digital technology and corporate carbon performance.

**Hypothesis 2a:** Green technology innovation plays a mediating role between digital technology and corporate carbon performance.

**Hypothesis 2b:** Green collaborative innovation plays a mediating role between digital technology and corporate carbon performance.

## 2.3 Regulatory role of environmental information disclosure

Enterprises are not independent entities in the market environment; their strategic behavior is influenced by multiple factors from within and outside. Environmental information disclosure, as the primary means for an enterprise to demonstrate its environmental situation and level of environmental governance to the outside world, will impact its green strategy implementation (Zhang J. et al., 2024) and industrial structural adjustment, whether of high or low quality (Liu et al., 2021). According to signaling theory, disclosing environmental information can reduce information asymmetry and opacity, enabling other parties to better understand a company’s environmental pollution data (Ye et al., 2023); it also serves as a monitoring mechanism (Cheng et al., 2017). Faced with scrutiny from external parties, companies are motivated to engage in various carbon reduction initiatives, prompting them to leverage digital technology to improve quality and efficiency in the dissemination of environmental information (Zhang Y. J. et al., 2024). This, in turn, enhances corporate reputation and garners public support (Zhang et al., 2023). It also attracts external investment (Pan et al., 2023) and integrates corporate information internally, enabling companies to break away from traditional path dependency and empowering them to upgrade their strategies, thus reducing short-sighted corporate management and focusing on more long-term sustainable strategic goals, and so improving carbon performance. Accordingly, the research proposes this hypothesis:

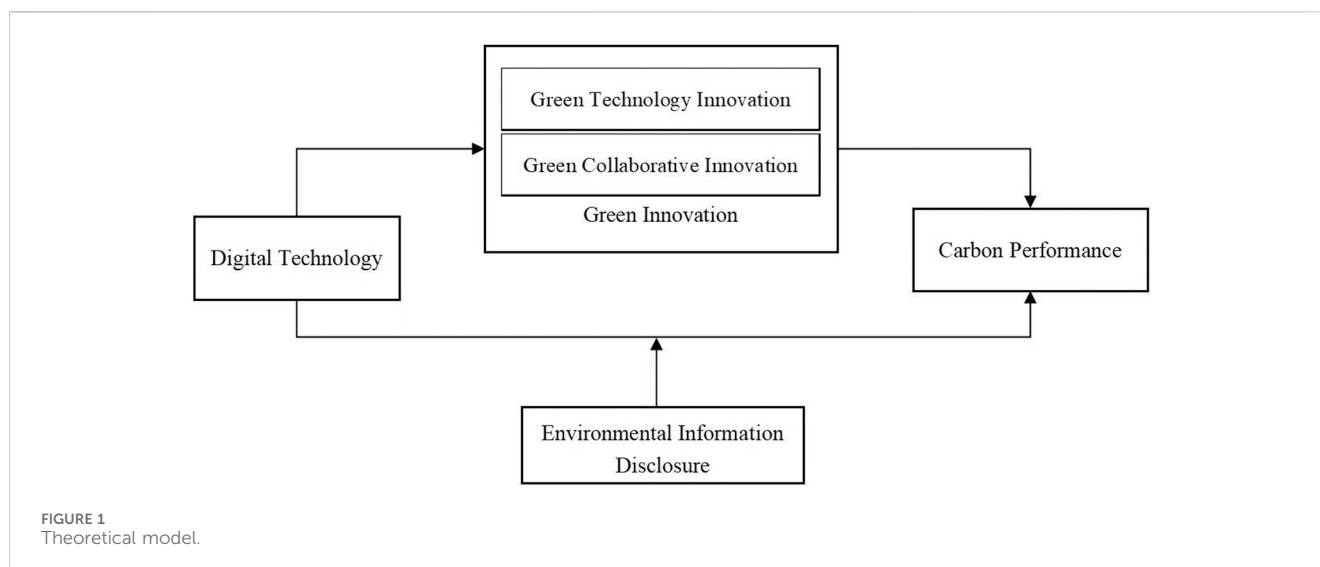
**Hypothesis 3:** The influence of digital technology on company carbon performance can be amplified through environmental information disclosure.

Figure 1 depicts the paper’s theoretical model.

## 3 Methodology and data

### 3.1 Sample selection and data source

This study utilizes panel data from China’s A-share listed manufacturing enterprises from 2012 to 2021 as the research sample. The data measuring digital technology and carbon performance come from the CSMAR database, while the data on green innovation are obtained from the CNRDS. Additionally, the data on environmental disclosure are collected from listed companies’ annual reports and China Provincial Databases, and data on other firm-level variables are organized from the CSMAR, CNRDS, and RESSET databases. The study processed the relevant data for the aim of ensuring the availability of the data as follows: 1) excluding ST, \*ST, PT, and terminated-listed firms during the study period; 2) excluding insolvent and missing-data samples; 3) all continuous variables are subjected to standard shrinkage between



1% and 99%. Balanced panel data consisting of 16,876 observations were thus obtained.

## 3.2 Variable measurement

### 3.2.1 Dependent variable: carbon performance (CPEP)

Given that businesses are unlikely to voluntarily disclose their carbon emissions, this paper indirectly estimates enterprise carbon emissions by using the industry's carbon emissions as a reference (Ding et al., 2023). It calculates the data by dividing the ratio of the enterprise's operating income per million yuan to its carbon emissions by 100, using revenue per unit of carbon emissions as a proxy for the enterprise's carbon performance (CPEP) (Gao et al., 2024). The specific calculations are reflected in Eqs 1, 2 below:

$$\text{Corporate carbon emission} = \frac{\text{Enterprise operating costs}}{\text{Industry operating costs}} \times \text{Industry carbon emission}, \quad (1)$$

$$\text{Carbon per formance (CPEP)} = \frac{\text{Enterprise operating income}}{\text{Corporate carbon emission} \times 100} \quad (2)$$

### 3.2.2 Independent variable: digital technology (LDIGTA)

The annual reports of enterprises can reflect their strategic directions; therefore, most research uses text analysis to measure the degree of the digitization of enterprises by analyzing the number of words related to numbers in their annual reports (Wen et al., 2022). In comparison with other methods, the text analysis method can comprehensively reflect the degree of digital technology adoption by microenterprises. Therefore, this paper draws on Qi et al. (2024) to organize specific keywords related to digital technology and categorize them into two dimensions based on the previous analysis. One dimension is the application of digital technology, which focuses on its implementation. The other

dimension is the research and development of digital technologies such as AI, blockchain, cloud computing, and big data (Yu and Tang, 2023). The keywords are summarized in Table 1. Expressions with negative words such as "no" before the keywords are eliminated. This paper then summarizes and extracts the annual reports of all A-share listed enterprises using Python software. It calculates the frequency of keywords in the annual reports as a measure of digital technology (LDIGTA). Then, based on the keyword phrases in Table 1, the word frequencies are summed up and subjected to logarithmic processing. A higher value indicates a higher level of an enterprise's digital technology.

### 3.2.3 Mediating variable: green innovation (LGrTeIn, LGrCoIn)

Numerous studies have used the number of green patent applications by enterprises as an indicator of the level of green innovation and innovation within enterprises (Zhang and Zhao, 2023; Di et al., 2024). Green application patents usually cover green invention and utility patents. More innovative green invention patents are a better indicator of the quality of green innovation than green utility patents. Therefore, for green technology innovation (LGrTeIn), we calculate the number of green invention patents filed independently by listed companies plus one to take the logarithm. Then we measure green collaborative innovation (LGrCoIn) by the number of jointly filed green invention patents plus one taking the logarithm.

### 3.2.4 Moderating variables: environmental information disclosure index (EDI)

This paper refers to the research of Kong et al. (2021), which classifies the disclosure of environmental information according to whether it is monetized, and divides monetized and non-monetized information into five dimensions according to scoring criteria: environmental responsibility, performance and governance, management, regulations and certifications, and disclosure channels (scores are assigned to each



TABLE 1 digital technology keywords.

Category	Dimensions	Keywords
Digital technology application dimension	Artificial intelligence technology	Artificial Intelligence, business intelligence, image understanding, investment decision aid system, intelligent data analysis, intelligent robot, machine learning, deep learning, semantic search, biometrics, face recognition, speech recognition, identity verification, autopilot, and natural language processing
	Big data technology	Big data, data mining, text mining, data visualization, heterogeneous data, credit reporting, augmented reality, mixed reality, and virtual reality
	Cloud computing technology	Cloud computing, stream computing, graph computing, memory computing, multi-party security computing, brain-like computing, green computing, cognitive computing, convergence architecture, billion-level concurrency, EB-level storage, internet-of-things, and information physics systems
	Block chain technology	Blockchain, digital currency, distributed computing, differential privacy technology, and smart financial contracts
Digital technology R&D dimensions	Applications of digital technology	Mobile internet, industrial internet, mobile internet, internet medical, e-commerce, mobile payment, third-party payment, NFC payment, intelligent energy, B2B, B2C, C2B, C2C, O2O, internet, intelligent wear, intelligent agriculture, intelligent transportation, intelligent medical, intelligent customer service, intelligent home, intelligent investment, intelligent travel, intelligent environmental protection, smart grid, intelligent marketing, digital marketing, unmanned retail, internet finance, digital finance, Fintech, financial technology, quantitative finance, and open banking

TABLE 2 Variable definitions.

Variable type	Variable	Variable name	Variable measurement
Dependent variable	CPER	Carbon performance	(Enterprise operating income/corporate carbon emissions)/100
Independent variable	LDIGTA	Digital technology	Ln (sum of frequency of digital technology keywords +1)
Mediating variable	IGreTeln	Green technology innovation	Ln (number of green invention patents filed independently by listed companies +1)
	IGreColn	Green collaborative innovation	Ln (number of joint applications for green invention patents +1)
Moderating variables	EDI	Environmental information disclosure	Ln (environmental disclosure score)
Control variables	Growth	Revenue growth rate	(Current year's operating revenue/previous year's operating revenue)-1
	ListAge	Listed years	Ln (year of listing - year of listing+1)
	M share	Management shareholding ratio	Management shareholding data/total share capital
	Tobin Q	Tobin's Q	(Market value of outstanding shares + number of non-tradable shares × net assets per share + book value of liabilities)/total assets
	RDEX	R&D intensity	Ln (logarithm treatment of R&D investment)
	Balance1	Shareholding checks and balances	Shareholding ratio of the second largest shareholder/shareholding ratio of the largest shareholder
	REC	Accounts receivable ratio	Net accounts receivable/total assets
	GEAr	Solvency	Total liabilities at the end of the year/total assets at the end of the year

dimension—Guo et al. (2023)), and sums up and logarithmically processes the data as a measure of the environmental information disclosure index (EDI).

### 3.2.5 Control variables

Drawing on existing research and the characteristics of listed manufacturing enterprises, the following control variables are selected: 1) revenue growth rate (Growth); 2) listed years (ListAge); 3) management shareholding ratio (M share); 4) Tobin's Q (Tobin Q); 5) research and development intensity (RDEX); 6) shareholding checks and balances (Balance1); 7)

accounts receivable ratio (REC); 8) solvency (GEAr). The variable definitions of the main research variables are presented in Table 2.

## 3.3 Regression models

### 3.3.1 Baseline model

This paper builds the benchmarking model to validate the effect of digital technology on carbon performance:

$$CPER_{it} = \alpha_0 + \alpha_1 LDIGTA_{it} + \alpha_2 Controls_{it} + \mu_i + \gamma_t + \epsilon_{it}, \quad (3)$$

TABLE 3 Descriptive statistics of major variables.

Variable	N	Mean	SD	Min	Max
CPER	16,876	9.153	11.73	0.027	62.60
LDIGTA	16,876	1.288	1.273	0	5.037
LGreTeln	16,876	0.281	0.691	0	6.328
LGreCoIn	16,876	0.078	0.320	0	2.303
EDI	16,876	2.999	0.396	2.398	3.951
Growth	16,876	0.172	0.320	-0.476	2.077
ListAge	16,876	1.837	0.927	0	3.367
M share	16,876	2.098	1.245	0.840	9.817
Tobin Q	16,876	0.183	0.214	0	0.726
RDEX	16,876	18.05	1.328	13.56	22.22
Balance1	16,876	0.383	0.283	0.008	1
REC	16,876	0.136	0.091	0.001	0.437
GEAr	16,876	0.369	0.182	0.033	0.811

where  $i$  denotes the listed company,  $t$  denotes time,  $CPER_{it}$  denotes the carbon performance of firm  $i$  in year  $t$ ,  $LDIGTA_{it}$  stands for the digital technology of firm  $i$  in year  $t$ ,  $Control_{it}$  is the aggregate of control variables,  $\mu_i$  stands for the individual fixed effect,  $\gamma_t$  stands for the time fixed effect, and  $\epsilon_{it}$  specifies the random error terms.

### 3.3.2 Mediation model

The following mediation effect model is constructed on the basis of Eq. 3 for further empirical testing:

$$LGre_{nit} = \beta_0 + \beta_1 LDIGTA_{it} + \beta_2 Controls_{it} + \mu_i + \gamma_t + \epsilon_{it}, \quad (4)$$

$$CPER_{it} = \varphi_0 + \varphi_1 LDIGTA_{it} + \varphi_2 LGre_{nit} + \varphi_3 Controls_{it} + \mu_i + \gamma_t + \epsilon_{it}. \quad (5)$$

Here,  $LGre_{nit}$  denotes the mediating variable green innovation ( $n = 1, 2$ ), which stands for green technology innovation  $LGreTe_{it}$  and green co-innovation  $LGreCo_{it}$ ; the definitions of the other variables are not different from Eq. 3.

### 3.3.3 Moderating model

To deeply explore the effect of the interaction between environmental information disclosure and digital technology disclosure of manufacturing firms on carbon performance, this study adds a centered interaction term ( $\overline{LDIGTA_{it}} \times \overline{EDI_{it}}$ ) to the model to obtain the econometric model thus:

$$CPER_{it} = \theta_0 + \theta_1 LDIGTA_{it} + \theta_2 EDI_{it} + \theta_3 (\overline{LDIGTA_{it}} \times \overline{EDI_{it}}) + \theta_4 Controls_{it} + \mu_i + \gamma_t + \epsilon_{it}, \quad (6)$$

where  $EDI_{it}$  indicates environmental information disclosure,  $\theta_3$  denotes the interaction utility,  $\theta_3 > 0$  stands for environmental

information disclosure that positively strengthens the role of digital technology on firms' carbon performance and  $\theta_3 < 0$  is a negative regulation. The rest of the variables are as per Eq. 3.

In this paper, the VIF test was performed prior to the benchmark regression; all the VIF values were less than 2, indicating no significant multicollinearity between variables. The Hausman test and F-test were then conducted. Synthesizing the test results, we chose the fixed effects model for estimation. The descriptive statistics of major variables in Table 1 are presented in Table 3.

## 4 Empirical results and analysis

In this section, the results of models (3)–(6) for the two-way fixed-effects model are derived, along with all regressions with clustered standard errors at the firm level; they are compared with earlier findings. Next, robustness tests are then conducted to mitigate endogeneity issues. Finally, heterogeneity in firm nature and strategic aggressiveness is explored.

### 4.1 Benchmark regression results and robustness tests

#### 4.1.1 Benchmark regression results

Table 4 presents the baseline regression analysis of the influence of digital technology on carbon performance. Column 1 reports the influence of digital technology on firms' carbon performance while controlling only for individuals and time; the coefficient of the direct effect of digital technology on firms' carbon performance is 0.604. Column 2 incorporates control variables. These results suggest that the influence of digital technology on corporate carbon performance is consistently positive whether or not control variables are included, which aligns with the findings of Wen et al. (2022), Chen et al. (2024a), and Liu H. et al. (2024). It also verifies Hypothesis 1, indicating that manufacturing industry enterprises can leverage digital technology to enhance enterprise carbon performance.

Furthermore, according to the regression analysis of control variables, it can be seen that a firm's years on the market, Tobin's Q, a firm's solvency, equity checks and balances, and R&D intensity can all positively contribute to a firm's carbon performance, with coefficients of 0.898, 0.240, 3.386, 1.154, and 0.337, respectively. This may be because the longer a company is listed, the greater its potential for growth, the higher its overall value, and the greater its investment in R&D. This indicates that the company is more capable of promoting the decoupling of its economy and carbon emissions and that it can actively invest more resources in carbon reduction activities, resulting in better carbon performance. Conversely, the growth rate of a firm's operating income and proportion of accounts receivable negatively affect its carbon performance, with coefficients of -0.505 and -4.409, suggesting that a higher level of investment and production operation will lead to poorer carbon performance. In terms of shareholding structure, management shareholding is detrimental to a company's carbon performance, while equity stability can enhance it. A high management shareholding ratio indicates that they have significant and unrestricted control over the company's governance. This increases the likelihood of the

TABLE 4 Benchmark regression results.

Column order	(1)	(2)
Variable	CPER	CPER
LDIGTA	0.604*** (0.110)	0.538*** (0.108)
Growth		-0.505** (0.180)
ListAge		0.898** (0.285)
Mshare		-1.690 (1.227)
TobinQ		0.240** (0.083)
RDEX		0.337* (0.176)
Balancel		1.154* (0.650)
REC		-4.409** (2.116)
GEAr		3.386*** (0.894)
Clustering enterprise SE	YES	YES
Individual FE	YES	YES
Year FE	YES	YES
N	16,876	16,876
R-squared	0.321	0.330

\* $p < 0.1$ , \*\* $p < 0.05$ , and \*\*\* $p < 0.01$ . Standard error statistics are in parentheses. The following table is the same.

management being more short-sighted and making decisions in favor of their own interests, thereby potentially neglecting the long-term interests and sustainability of the enterprise (Wang Z. R. et al., 2023). Hence, shareholding checks and balances are beneficial for an enterprise in aligning its strategic vision with a more sustainable path of development, ultimately enhancing its overall carbon performance.

#### 4.1.2 Robustness test

Robustness tests were conducted, with the results presented in Table 5 to ensure the credibility of the model estimation results.

The first was an endogenous test. Considering the existence of a certain reverse causality between digital technology and enterprise carbon performance, which leads to the endogeneity problem, this paper adopts the instrumental variable method to deal with the problem. Considering that the level of digital technology in the industry in which the enterprise operates and the density of mobile base stations are closely related to the digital technology application by enterprises, and at the same time, it is also difficult to produce a

direct logistical correlation of the carbon performance of the enterprise, so this paper chose the average level of digital technology industry (ADAI) (Li and Shen, 2021) and the density of mobile base stations (MBSD) as the instrumental variables. The results are shown in columns 1 and 2 of Table 5, in which the weak instrumental variable and over-identification tests verify their relevance and exogeneity, respectively, and the regression results show that after overcoming the endogeneity problem, the positive impact of digital technology on corporate carbon performance is still significant, and the results are still robust.

There are, at the same time, more factors that affect carbon performance. The control variables selected in this paper are limited, so the problem of omitted variables may arise; this paper thus introduces the size of the firm (SIZE) and the level of economic development of the province in which the firm is located (REDL) as new control variables. The results are shown in column 3 of Table 5, where the coefficient before the numerical technical indicators is 0.527 and positively significant, so the results are robust.



TABLE 5 Robustness test.

Column order	(1) First	(2) second	(3)	(4)	(5)	(6)	(7)	(8)
Variable	LDIGTA	CPER	CPER	F. CPER	CPER	CPER	CPER	CPER
LDIGTA		19.205***	0.527***	0.423***		0.025**	0.282**	2.100***
		(9.20)	(0.117)	(0.122)		(0.011)	(0.087)	(0.144)
LDigApp					0.346**			
					(0.122)			
ADAI	0.027***							
	(9.50)							
MBSD	0.003*							
	(1.82)							
REDL			-1.818***					
			(0.493)					
SIZE			0.982**					
			(0.340)					
Control variable	YES	YES	YES	YES	YES	YES	YES	YES
Cluster enterprise SE	YES	YES	YES	YES	YES	YES	NO	NO
Clustering industry SE	NO	NO	NO	NO	NO	NO	YES	NO
Clustering city SE	NO	NO	NO	NO	NO	NO	NO	YES
Individual FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
N	16,297	16,297	15,450	13,689	16,876	4,439	16,876	16,861
R-squared			0.337	0.317	0.328	0.247	0.732	0.352
Kleibergen-Paap rk LM statistic		84.35***						
Kleibergen-Paap Wald rk F statistic		46.56						
Value of the 10% level in the Stock Yogo test		19.93						
Hansen J statistic		Chi-sq (1) = 0.3665						

We second replaced the dependent variables. Given that the current state of digital technology in manufacturing companies is likely to affect future carbon performance, this study substituted the dependent variables for future period data and re-ran the regression. The results are displayed in Column 4; the coefficient before the numerical technical indicator is 0.423 and positively significant, which is not different from the previous result.

Third, we replaced the independent variables. By comparing the two dimensions of the digital technology division—the digital technology application dimension and the digital technology R&D dimension—we selected the word frequency that represented the more specific digital technology application index (LDigAPP) as a replacement variable. The regression was then re-run. Column 5 shows the results, and so the coefficient for the digital technology (LDigAPP) indicator is 0.346, showing a positive relationship at the 5% level. This finding is consistent with the conclusions of the previous benchmark regressions.

Fourthly, non-heavy-polluting enterprises were excluded from the sample subregression. In manufacturing enterprises with significant emissions, high energy-consuming and heavily polluting enterprises account for a larger proportion of carbon emissions. Therefore, this paper categorizes the heavily polluting enterprises based on Pan et al. (2019) and examines whether digital technology will continue to enhance carbon performance in these enterprises after excluding the non-heavy polluting samples. Column 6 demonstrates that the coefficient of the effect of digital technology on carbon performance still behaves positively. Although it is slightly reduced in comparison, it is enough to show the credibility of the carbon reduction effect of digital technology on firms.

Lastly, we replaced the clustering robust standard error at the industry and city levels. From the results displayed in Columns 7 and 8, respectively, the coefficients of digital technology indicators do not change significantly in significance and sign after regrouping the standard errors at the industry and city levels. Although the coefficients clustered at the industry level for digital technology

TABLE 6 Mediation effect test results.

Column order	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Variable	LGreTeln	CPER	LGreTe	CPER	LGreCoIn	CPER	LGreCo	CPER
LDIGTA	0.021** (3.292)	0.528*** (4.894)	0.020** (2.671)	0.531*** (4.932)	0.007** (2.239)	0.533*** (4.966)	0.009** (2.287)	0.534*** (4.979)
LGreTeln		0.525** (2.718)						
LGreTe				0.356** (2.067)				
LGreCoIn						0.770** (2.329)		
LGreCo								0.471* (1.679)
Control variable	YES	YES	YES	YES	YES	YES	YES	YES
Cluster enterprise SE	YES	YES	YES	YES	YES	YES	YES	YES
Individual FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Bootstrap95% conf. interval	(0.0039,0.0203)		(0.0017,0.0147)		(0.0118,0.1236)		(0.0004,0.0107)	
N	16,876	16,876	16,876	16,876	16,876	16,876	16,876	16,876
R-squared	0.3303	0.0209	0.3314	0.0214	0.3310	0.0148	0.3311	0.0160

are slightly lower in magnitude and significance, digital technology still demonstrates a significant positive push on firms' carbon performance.

## 4.2 Mediation effect test

This paper used Eqs 4 and 5 to examine whether digital technology can impact corporate carbon performance through green innovation. The analysis was performed with stepwise regression as the main method, and a Bootstrap test was used to perform 1,000 sample regressions to further assist validation. Table 6 presents the mediation test results of green technology innovation and green collaborative innovation.

Columns 1 and 5 reveal the results of digital technology on green technological and green collaborative innovation. From the results, it is evident that the coefficients of digital technology are 0.021 and 0.007, respectively, and both are significant, suggesting that digital technology is capable of enhancing the level of green technological and collaborative innovation within companies, confirming Li et al. (2023) and Han et al. (2024). Furthermore, core explanatory variables were added in columns 2 and 6. The coefficients of digital technology and green technology innovation in column 2, digital technology and green collaborative innovation in column 6 are all significantly positive, with values of 0.528, 0.525, 0.533, and 0.770 respectively. The coefficients of digital technology are smaller than the main effect regression coefficients without intermediaries. In addition, the confidence interval adjusted for bias in the Bootstrap

test does not contain zero and shows a positive sign. Based on a variety of results, we comprehensively judge that there is a mediation effect. This means that digital technology can enhance carbon performance by ramping up independent green technology innovation and green collaborative innovation on behalf of R&D cooperation. Thus, Hypotheses 2a and 2b are both verified.

In order to further verify the existence of green innovation mechanisms, this study comprehensively considered green invention patents and green utility patents. It utilized the total amount of green patents independently applied by the company (LGreTe), the total amount of green patents jointly filed (LGreCo) plus one to take the natural logarithm as a replacement variable to re-measure the level of green technological and green innovation for regression. Results are shown in Columns 3, 4, 7, 8, respectively. Depending on the outcome, the coefficients and significance of the indicators of digital technology, green technology innovation, and green collaborative innovation do not produce significant changes.

Taken together, the results indicate that digital technology is capable of improving the carbon performance of firms by enhancing green innovation; thus Hypothesis 2 is confirmed. This is consistent with Dong et al. (2023) and Zhang et al. (2019) on the ability of green innovation to solve environmental problems in enterprises.

## 4.3 Moderating effect test

Environmental disclosure is taken as a moderating variable to test whether the influence of digital technology on carbon

TABLE 7 Regression results of the moderating effect of environmental information disclosure.

Column order	(1)	(2)
Variable	CPER	CPER
LDIGTA	0.538***	0.538***
	(5.007)	(4.993)
EDI		-0.301
		(-0.956)
LDIGTA× EDI		0.426**
		(2.361)
Control variable	YES	YES
Cluster enterprise SE	YES	YES
Individual FE	YES	YES
Year FE	YES	YES
N	16,876	16,876
R-squared	0.3303	0.3311

performance is swayed by environmental disclosure in this paper, and Eq. 6 is utilized to test the moderating effect. Column 2 of Table 7 shows the coefficient of the interaction term between environmental disclosure and digital technology as 0.426, indicating that environmental disclosure positively moderates the process of carbon performance enhancement by digital technology. Thus, the greater the quality of environmental disclosure by an enterprise, the more energy and resources enterprises will go into the behavior of carbon emission reduction in the face of supervision from outside subjects. This prompts the enterprise to take the initiative to seek ways to improve resource allocation methods, leading to the improvement of enterprise carbon performance. Hence, Hypothesis 3 is verified.

## 4.4 Heterogeneity analysis

The impacts of digital technology, green innovation, and environmental information disclosure on carbon performance vary across firms with different strategic aggressiveness due to their different nature and implementation strategies. Therefore, this paper conducted subgroup regressions on a sample of companies in various types of industry and with different levels of strategic aggressiveness.

### 4.4.1 Industry heterogeneity

Considering that manufacturing enterprises of different industry types will vary in their implementation of digital technology, the activities of green innovation, the disclosure of environmental information due to differences in their own conditions, and such variations will affect an enterprise's ability to reduce carbon emissions and increase efficiency. This paper categorizes the enterprise samples into high-tech and non-high-tech industries, based on their nature.

The industry heterogeneity analysis of the influence of digital technology on carbon performance is presented in Table 8. In Column (1), we can see that within the sample of high-tech industry firms, digital technology significantly boosts corporate carbon performance. Column 2 displays the regression result for non-high-tech industry enterprises, indicating a coefficient of 0.061 for the digital technology indicator; however, the result is not statistically significant. Thus, by comparing the two, high-tech industry enterprises are shown to have a greater potential for carbon reduction. This suggests that high-tech industry firms possess more human capital and advanced technology and equipment. They are also more likely to capitalize on opportunities in today's wave of digitization and utilize a variety of digital technologies to enhance their carbon performance level.

Table 9 presents the industry heterogeneity analysis of the two mediating mechanisms. It is apparent that digital technology can enhance the carbon performance of high-tech industry enterprises through two pathways: green technology and green collaborative innovation. However, the mediating effects of these do not exist in non-high-tech industry enterprises, because there is a superior level of technology and pollution control in high-tech industry firms, coupled with government encouragement of the promotion and development of high-tech technology, they have more resources and policy support, and therefore digital technology can facilitate the two channels of green innovation, leading to higher levels of companies' carbon performance.

Table 10 presents the findings of an industry heterogeneity analysis of environmental information disclosure. This indicates that environmental disclosure can positively influence carbon performance driven by digital technology, regardless of whether they are in high-tech industries, although the moderating effect is better in high-tech industries. This is because high-tech companies themselves are a focus of the public and the government, and their level of environmental disclosure can convey the positive information of the enterprise to the outside world and become a favorable tool for the enterprise to enhance its competitiveness. This prompts the enterprise to take the initiative to use digital technology and other means to enhance its carbon performance. In contrast, non-high-tech manufacturing enterprises are constrained by resource availability, policy conditions, and digitalization construction, which limit their ability to fully leverage environmental information disclosure to regulate digital technology and promote carbon performance.

### 4.4.2 Heterogeneity of strategic aggressiveness

An enterprise's development strategy is an important motivator for the construction and development of digital technology in manufacturing enterprises. Its development objectives and business directions are affected by different degrees of strategic aggressiveness (Weinzimmer et al., 2023). Enterprises with low degrees of strategic aggressiveness tend to choose a more prudent development strategy to ensure the maintenance of the existing business performance. Enterprises with a high degree of strategic aggressiveness tend to pursue the maximization of benefits, which will inevitably have different impacts on how companies build digital technology, green innovation, and environmental disclosure, which in turn affects their carbon performance. For the purpose of verifying this, this study passed through the steps

TABLE 8 Industry heterogeneity test of the impact of digital technology on carbon performance.

Column order	(1) High-tech industries	(2) Non-high-tech industries
Variable	CPER	CPER
LDIGTA	0.567*** (4.545)	0.061 (1.343)
Control variable	YES	YES
Cluster enterprise SE	YES	YES
Individual FE	YES	YES
Year FE	YES	YES
N	13,503	3,366
R-squared	0.3919	0.1509

TABLE 9 Industry heterogeneity testing of green technology innovation and green collaborative innovation mechanisms.

Column order	(1) High-tech industries	(2) High-tech industries	(3) Non-high-tech industries	(4) Non-high-tech industries	(5) High-tech industries	(6) High-tech industries	(7) Non-high-tech industries	(8) Non-high-tech industries
Variable	LGreTeln	CPER	LGreTeln	CPER	LGreColn	CPER	LGreColn	CPER
LDIGTA	0.024** (3.164)	0.554*** (4.433)	0.011 (1.078)	0.060 (1.323)	0.009** (2.366)	0.561*** (4.508)	-0.001 (-0.101)	0.061 (1.344)
LGreTeln		0.531** (2.628)		0.096 (1.010)				
LGreColn						0.646* (1.838)		0.058 (0.583)
Control variable	YES	YES	YES	YES	YES	YES	YES	YES
Cluster enterprise SE	YES	YES	YES	YES	YES	YES	YES	YES
Individual FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
N	13503	13503	3366	3366	13503	13503	3366	3366
R-squared	0.0240	0.3929	0.0145	0.1513	0.0178	0.3924	0.0126	0.1509

of sorting, assigning, and summing up the six dimensions of innovation tendency, market expansion tendency, growth, production efficiency, organizational structure, and capital density. These are divided into three groups—defensive, analytical, and offensive strategies—based on their total scores, with the degree of aggressiveness increasing in turn (Wang J. X. et al., 2023).

The results of the heterogeneity test for the strategic aggressiveness of the impact of digital technology on firms' carbon performance are shown in Table 11. These demonstrate that digital technology can help companies with defensive and analytical strategies improve their carbon performance. However, it has a negative but not significant impact on the carbon-

performance—implementing offensive strategies, with a coefficient of -0.113. This is because offensive enterprises are more inclined to open up new markets and strive for higher economic benefits, therefore increasing the utilization and flow rate of resources; this in turn increases carbon emissions and is not conducive to the carbon performance of enterprises.

Tables 12 and 13 show the analysis of the heterogeneity of the strategic aggressiveness of the two mediating mechanisms. The results suggest that the two mediating paths—green technology innovation and green collaborative innovation—can only work in enterprises that implement analytical strategies, but they do not exist in enterprises that implement both defensive strategies and offensive strategies. This is because enterprises focus more on short-term

TABLE 10 Industry heterogeneity testing of regulatory mechanisms.

Column order	(1) High-tech industries	(2) Non-high-tech industries
Variable	CPER	CPER
LDIGTA	0.576***	0.033
	(4.630)	(0.707)
EDI	-0.340	0.368
	(-0.911)	(1.424)
LDIGTA× EDI	0.577**	0.353**
	(2.780)	(2.638)
Control variable	YES	YES
Cluster enterprise SE	YES	YES
Individual FE	YES	YES
Year FE	YES	YES
N	13,503	3,366
R-squared	0.3930	0.1629

TABLE 11 Heterogeneity test of strategic incentive progress of the impact of digital technology on carbon performance.

Column order	(1) Defensive strategy	(2) Analytical strategy	(3) Offensive strategy
Variable	CPER	CPER	CPER
LDIGTA	1.011**	0.512***	-0.113
	(3.051)	(3.766)	(-0.274)
Control variable	YES	YES	YES
Cluster enterprise SE	YES	YES	YES
Individual FE	YES	YES	YES
Year FE	YES	YES	YES
N	997	9,443	874
R-squared	0.3285	0.3250	0.2557

economic benefits when implementing defensive strategies and will neglect their environmental performance in order to avoid risks and reduce resource inputs. On the other hand, enterprises that implement offensive strategies may increase resource demand in pursuit of higher economic benefits, which is also not conducive to improving carbon performance.

Table 14 shows the findings of strategic aggressiveness heterogeneity analysis on the moderating impact of environmental disclosure. This indicates that in companies that implement analytical strategies, environmental disclosure can positively influence the adoption of digital technology to enhance corporate carbon performance. However, environmental disclosure did not have such a moderating effect in firms with defensive and offensive strategies. This suggests that higher-quality environmental disclosure in companies that implement analytical strategies is more beneficial for leveraging digital technology to enhance corporate carbon performance.

## 5 Conclusion and implications

### 5.1 Conclusion

Based on the realistic scenarios now driving the digitalization and green low-carbon transformation of firms, this study empirically explored data from China's A-share listed manufacturing enterprises for 2012–2021 by adopting a fixed-effects model through resource coordination and signaling theories. Specific studies include the impact of digitalization technology on the carbon performance of manufacturing companies, the dual intermediary mechanism of green technological and green collaborative innovation, and the moderating role of environmental information disclosure. From these empirical results, the conclusions and contributions follow thus.



TABLE 12 Heterogeneity test of the strategic incentive progress of the green technology innovation mechanism.

Column order	(1) Defensive	(2) Defensive	(3) Analytical	(4) Analytical	(5) Offensive	(6) Offensive
Variable	LGreTeln	CPER	LGreTeln	CPER	LGreTeln	CPER
LDIGTA	0.011	1.107**	0.026**	0.560***	-0.020	-0.060
	(0.381)	(3.179)	(2.949)	(4.140)	(-0.612)	(-0.150)
LGreTeln		-0.014		0.774**		-1.666*
		(-0.036)		(2.948)		(-1.899)
Control variable	YES	YES	YES	YES	YES	YES
Cluster enterprise SE	YES	YES	YES	YES	YES	YES
Individual FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
N	997	997	9,443	9,443	874	874
R-squared	0.0525	0.3027	0.0237	0.3076	0.0377	0.2291

TABLE 13 Heterogeneity test of the strategic stimulation progress of the green collaborative innovation mechanism.

Column order	(1) Defensive	(2) Defensive	(3) Analytical	(4) Analytical	(5) Offensive	(6) Offensive
Variable	LGreColn	CPER	LGreColn	CPER	LGreColn	CPER
LDIGTA	0.045**	1.095**	0.010**	0.573***	-0.001	-0.029
	(2.045)	(3.210)	(2.061)	(4.252)	(-0.055)	(-0.073)
LGreColn		0.233		0.887**		-0.055
		(0.304)		(2.360)		(-0.046)
Control variable	YES	YES	YES	YES	YES	YES
Cluster enterprise SE	YES	YES	YES	YES	YES	YES
Individual FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
N	997	997	9,443	9,443	874	874
R-squared	0.0576	0.3029	0.0173	0.3062	0.0271	0.2189

- (1) Digital technology can help companies improve their carbon performance, and the results remain valid after various robustness tests. In other words, digital technology can help businesses maximize the value of data, optimize resource utilization processes, and promote sustainable enterprise development.
- (2) Digital technology can promote the enhancement of enterprise carbon performance through the two intermediary mechanisms of green technology innovation and green collaborative innovation. Enterprises can break the information shackles by utilizing digital technology to obtain green core competitiveness and promote their own and cross-principal green innovation activities, which then helps them enhance their carbon performance.
- (3) Environmental information disclosure shows a positive moderating impact in the process of promoting enterprise

- carbon performance by digital technology. Environmental disclosure can decrease the asymmetry and opacity of information externally, so that in the face of public supervision and government regulation, it can focus on long-term sustainable development, take the initiative to launch the construction of digital technology, and enhance firms' carbon performance.
- (4) Differences in the nature of industries and the aggressiveness of enterprises' implementation strategies lead to heterogeneity in the impacts of digital technology, green innovation, and environmental information disclosure on carbon performance. Specifically, when considering industry heterogeneity, the effectiveness of digital technologies to improve carbon performance, green innovation, and environmental disclosure are more significant for high-tech industry enterprises. Additionally, when considering the heterogeneity of enterprise strategic

TABLE 14 Heterogeneity test of strategic stimulation progress in regulatory mechanisms.

Column order	(1) Defensive	(2) Analytical	(3) Offensive
Variable	CPER	CPER	CPER
LDIGTA	0.915**	0.473***	-0.111
	(2.454)	(3.424)	(-0.247)
EDI	1.590*	-0.154	-2.645*
	(1.871)	(-0.386)	(-1.922)
LDIGTA× EDI	0.405	0.730**	0.077
	(0.711)	(3.031)	(0.094)
Control variable	YES	YES	YES
Cluster enterprise SE	YES	YES	YES
Individual FE	YES	YES	YES
Year FE	YES	YES	YES
N	997	9,443	874
R-squared	0.3334	0.3271	0.2635

aggressiveness, digital technology shows a better ability to improve carbon performance in companies with defensive and analytical strategies than companies with offensive strategies, while the character of green innovation as a mediator and environmental disclosure as a moderator is more significant among firms with analytical strategies.

## 5.2 Implications

The following useful insights are obtained by this study based on the empirical results.

First, manufacturing companies should concentrate on the carbon reduction potential of digital technologies, build their digital talent pipeline and infrastructure, and apply it to more enterprise development areas. They should also establish a green innovation system around digital technology and proactively ramp up the quality of environmental information disclosure, which supports improving their carbon performance. Manufacturing businesses should also base their decisions on their current state, the characteristics of their sector, and the application of a plan to create a carbon performance improvement plan. To support the complete implementation of carbon reduction goals, non-high-tech industrial firms should expedite the creation of digital technology and green innovation investment. Businesses that adopt more aggressive or conservative strategies should also adopt digitalization and greening practices appropriate to their own elemental structure and strategic goals. They should also avoid placing undue emphasis on short-term financial gains and high performance in exchange for environmental harm and instead ensure their own sustainable development.

Second, the manufacturing industry should fully consider the characteristics of the industry and the law of development, the

development of differentiated digitalization and green transformation programs, and the scientific promotion of digital technology infrastructure. They should do so focusing on enterprise-independent green technology research and development, the construction of a multi-body green R&D cooperative platform, and rely on the platform of synergistic innovation results to promote the whole manufacturing industry, the whole chain of digitalization, and green transformation.

Third, local governments should increase support for the digital technology construction and green innovation activities of manufacturing enterprises. Government should consider factors such as type of industry and degree of a company's development to establish precise and differentiated support policies to expedite the promotion of digital and green transformation in traditional manufacturing enterprises. It should also more intensively supervise enterprises' environmental information disclosure and formulate corresponding warning and punishment rules. Moreover, government can improve innovation incentive policies, provide incentives for enterprise innovation behavior—such as subsidies, tax incentives, or technical support—and actively promote inter-enterprise innovation cooperation to guide the construction of digital technology and green innovation for manufacturing enterprises and even the whole industry, thereby promoting the transformation of China's manufacturing industry into a low-carbon economy, facilitating the implementation of China's "dual-carbon" target program, and thus contribute to the mitigation of environmental problems caused by global carbon emissions.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

## Author contributions

JL: writing–review and editing. LJ: writing–review and editing and writing–original draft. SZ: writing–review and editing. YZ: writing–review and editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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