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# How Does the Digital Transformation Affect the Carbon Emissions of Manufacturing Enterprises in China? The Perspective of Green Technology Innovation

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**Abstract:** With the continuous intensification of competition among major countries and the resurgence of anti-globalization trends, countries around the world have strengthened their strategic deployment for digital transformation in the manufacturing industry. Digital development enables enterprises to transform and upgrade, and the digital transformation and green transformation of enterprises have a historic intersection. This study uses the panel data of 1900 A-share listed companies to explain the theoretical mechanism of digital transformation to promote carbon emission reduction from the perspective of green technology progress. In addition, the threshold model is used to analyze the nonlinear relationship. The results show that the digital transformation has significantly reduced the carbon emission level of Chinese manufacturing enterprises, and the conclusion is still true after the instrumental variable estimation and robustness test. Heterogeneity analysis found that the carbon emission reduction in state-owned enterprises is more obvious. Green technology innovation capability shows the technology dividend effect, which is an important way for digital transformation to promote carbon emission reduction. This study expands the research on the sustainable development of China's manufacturing industry and provides guidance for policy makers and business decision makers.

**Keywords:** digital transformation; carbon emissions; green technology innovation; sustainable development



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## 1. Introduction

The accumulation of carbon dioxide has brought some negative effects, causing harm to human health and ecosystems [1]. The world has recognized the extent and consequences of carbon impact on global climate change; therefore, it has been conducting some research, tracking, disposal, and response for many years. Governments around the world are actively concerned about global warming and take active measures to reduce environmental pollution. The specific challenges faced by China in its transition to a low-carbon economy are multifaceted. The contribution rate of China's secondary industry to GDP is about 40%, while energy consumption accounts for about 68%. This industrial structure puts enormous pressure on China to reduce carbon emissions. Coal is the main source of energy in China, accounting for 56% of the total energy consumption in 2021. This energy structure leads to enormous incremental pressure on greenhouse gases, posing a significant challenge to low-carbon transformation. China's energy intensity is about 1.5 times the global average, which means there is still a large amount of room for improvement in energy utilization efficiency and energy conservation and emission reduction. As a high emission country, China needs to achieve large-scale emission reduction within a limited time window and complete the comprehensive green and low-carbon transformation of its economy and society, which is undoubtedly a challenging task. The Chinese government has made a serious commitment: by 2030, China's carbon emissions will be reduced from 60% to 65% compared with 2005, and it is proposed to achieve carbon neutrality by 2060 [2]. The Chinese government emphasizes the priority of ecological environment and has made work arrangements for the comprehensive green transformation of the economy and society in the future. These measures include strengthening carbon reduction actions, promoting renewable energy, etc., in order to achieve coordinated promotion of high-quality economic development and high-level protection of the ecological civilization. The development of China's manufacturing industry is not only reflected in the economic level, but also related to the status of the country and people's lives. China ranks first in the world in terms of manufacturing scale with its own potential and unique advantages [3]. In the future, with the rapid economic development, if this industry continues to adopt an extensive development model, its impact on the ecological environment will continue to expand, seriously affecting the sustainable use of resources and the environment in which people live. Carbon peaking and carbon neutralization are both opportunities and challenges for the manufacturing industry. Only by making full use of digital technology can manufacturing enterprises walk more steadily and effectively on the path of digital and low-carbon collaborative development. Digital transformation is undoubtedly the best choice. At present, China's manufacturing enterprises have begun many beneficial explorations, which is worth studying.

The application of digital technology helps enterprises determine the direction, potential, and path of green technology innovation [4]. Digitalization is an important means to reduce carbon emissions at present, and the promotion of greening is inseparable from digitalization. The green transformation needs solid digital technology as support [5]. For example, enterprises can promote the degree of enterprise informatization, increase social influence, and optimize corporate structure to promote green technology innovation through digital transformation [6]. However, enterprises' green technology innovation investment is an investment form with unique characteristics, which requires enterprises to fully consider its unique characteristics in the investment processes, perform a good job in risk management, and actively explore suitable investment and financing modes. More research on how green technology innovation promotes the low-carbon transformation of manufacturing industry is needed to provide new insights for enterprises and government decision-making.

However, previous literature has mainly focused on the relationship between digital transformation and carbon emissions. Scholarship has yet to combine the development level of digital transformation, green technology innovation, and carbon emissions to examine their dynamic relationship. This indicates that research into the specific mechanism of green innovation between digital transformation and carbon emissions is still inadequate. Therefore, our research offers a fresh perspective to reveal the pivotal role of green technology innovation. As digital transformation of enterprises has a positive impact on enhancing the efficiency of green technology innovation, and both may have an impact on carbon emissions, we can infer that green technology innovation may be a crucial mediator between digital transformation and carbon emissions. Additionally, the impact of enterprise digital transformation on carbon emissions is both directly and indirectly influenced by green technology innovation. Furthermore, green technology innovation may have both positive and negative impacts on carbon emissions. Therefore, when considering green technology innovation, the impact of digital transformation on carbon emissions may exhibit nonlinear characteristics.

Compared to previous studies, this paper adds to the research on the relationship between the digital transformation of manufacturing enterprises, green technology innovation, and the carbon emissions of manufacturing enterprises. First, an extended STIRPAT model is constructed by introducing enterprise digital transformation, which serves as the benchmark model. Second, green technology innovation is taken as a mediator to explore its emission reduction effect. Third, the nonlinear relationship between enterprise digital transformation and carbon emissions is explored. This paper discusses the nonlinear effect of enterprise digital transformation on carbon emission reduction. In contrast to previous studies, this study emphasizes the crucial role of green technology innovation. Through digital transformation, enterprises can enhance production efficiency, optimize energy usage, and minimize environmental pollution, thus achieving sustainable development. Green technology innovation also supports enterprises' digital transformation. Additionally, this study provides practical guidance and suggestions for decision makers and enterprise decision makers.

This paper focuses on the digital transformation, green technology innovation, and carbon emissions of manufacturing enterprises. It delves into four gradual questions:

RQ1. Can digital transformation effectively curb carbon emissions?
RQ2. Can green technology innovation serve as a mediating variable?
RQ3. Is the impact of digital transformation on carbon emissions nonlinear?
RQ4. What is the impact of different property rights on carbon emissions?

To answer the above questions, the following sections of this paper are structured as follows: the second section organizes previous research results and advances the theoretical assumptions of this paper. The third section constructs an econometric model and explains the significance of the variables. The fourth section presents the empirical results, and guarantees the reliability of the research results through the robustness test. The fifth section discusses the research results. The sixth section summarizes the research results and proposes corresponding policy recommendations according to the actual environment.

## 2. Literature Review and Hypotheses

This section provides a review of relevant research on the impact of digital transformation and green technology innovation on carbon emissions, providing a basis for setting econometric models to respond to research questions and providing literature support for proposing research hypotheses.

### *2.1. Literature Review*

Although many scholars have noticed the carbon emission reduction benefits of enterprise digital transformation, there is no final conclusion about the relationship between the two and specific industries. The integration of real industry and digital industry will bring the superposition effect of digital value and commercial value, and realize the effect of three dimensions of open source, cost saving, and efficiency improvement. It has been reflected in the digital development of manufacturing industry. At present, many Chinese enterprises have achieved good results in environmental protection through advanced information technology [7]. Enterprises can make use of the advantages brought by digital transformation to enhance their comprehensive strength in business activities [8]. For example, enterprises can make full use of the advantages of digital finance, reduce the difficulty of enterprise financing, and provide financial support for technology upgrading [9]. In addition, the research of Shang et al. [10] shows that the objective of Chinese enterprises is to reduce carbon emissions through digital applications. The digital process of enterprises also indirectly broadens their technological innovation thinking, optimizes the overall production process, and improves the intensity of relevant information disclosure, thus significantly reducing the intensity of carbon emissions. Then, there are studies that show that the emission reduction effects brought by the digital transformation of different industrial sectors are obviously different [11], for example, the energy conservation and emission reduction in electric heating enterprises are not obvious [12]. Moreover, the rapid development of digital economy and the construction of necessary infrastructure have increased the consumption of energy, and caused the increase in carbon dioxide in its primary stage [13]. Therefore, the emission reduction effect of digital economy cannot be lumped together. Some scholars have pointed out the possible nonlinear characteristics between the two. Li et al. used the econometric model to prove that the carbon emission reduction effect of the digital economy of China's prefecture level cities presents an inverted U shape [14].

Yang's research shows that individual micro enterprises can use digital transformation to reduce environmental pollution incrementally [15].

According to Romer's endogenous economic growth theory, technological progress can promote economic development. Technological innovation guided by the connotation of green development reflects the dual goals of economic and ecological development. Under the guidance of the national green development concept, green technology innovation can effectively enhance the reduction in carbon emissions in the manufacturing industry. From a microscopic perspective, this is reflected in the fact that enterprises can use modern technologies such as big data, blockchain, and digital twins to carry out low-carbon transformation and upgrading of process and equipment, promote process innovation, management optimization, and equipment upgrading, and form a green production supply chain, thereby reducing carbon emissions in production processes [16]. From a macro perspective, green technology innovation can empower the comprehensive low-carbon transformation of the economy and society, thereby promoting low-carbon energy consumption [17]. Green technology innovation helps to promote the development of the green industry, promote the green transformation of traditional industries, and eliminate polluting industries, thereby improving energy efficiency, promoting the high-end and greenization of industrial structure, and helping to reduce carbon emissions [18].

The current research shows that the digital transformation of enterprises can promote the innovation of green technology. Digital technology has the ability of efficient analysis, which not only breaks the isolation between banks and enterprises, but also reduces the cost of green technology innovation and accelerates the conception and implementation of innovation projects for the exchange and sharing of enterprise resources and the absorption and diffusion of external knowledge [19]. Green technology innovation can enhance the innovation ability of advanced manufacturing industry, enhance its innovation output, and provide innovation guarantee for high-quality industrial development [20]. Green technology innovation can release the effect of energy conservation and emission reduction, promote the cleaning of industrial structure, update and improve machinery and equipment, improve the green manufacturing capacity of enterprises, and effectively reduce the environmental costs of enterprises [21]. Enterprises in green technology, green products, green technology, and other aspects are also increasingly mature, forming a virtuous circle of digital development and green technology innovation. At the same time, enterprises optimize talent management through digital transformation [22]. As an important resource for enterprise development, talent has become an important driving factor for enterprise green technology innovation. Zhang et al. [23], Ning et al. [24], and Lu et al. [9] pointed out that technological innovation provides a powerful driving force, and the "double carbon" goal provides an effective transmission path for industrial technological progress. Therefore, under the goal of "double carbon", green development can promote manufacturing enterprises to reduce environmental costs and resource use costs, promote the development of low-carbon economy, and then promote the high-quality development of advanced manufacturing enterprises.

From the above, it can be seen that existing research attempts to open up the "black box" of digital transformation and carbon emissions, in order to identify potential problems in China's green and low-carbon development. The digital transformation has strengthened the application of technology to a certain extent, but the mechanism of its impact on low-carbon development still needs to be further clarified. In particular, the mechanism of green technology innovation's impact on carbon emissions in the process of digital transformation still needs to be constructed. In view of this, based on existing literature research, this article will start from the relationship between digital transformation and low-carbon development, attempting to analyze the mechanism of green technology innovation in the impact of digital transformation on low-carbon development.

### 2.2. Research Hypothesis

#### 2.2.1. Direct Impact of Digital Transformation on Low-Carbon Transformation of Enterprises

Enterprise digital transformation refers to the introduction and application of digital technology to optimize the production process, innovate the management mode, and promote the upgrading and transformation of enterprise structure [25]. Digital transformation is a practice of using advanced technology to make the enterprise operation more efficient and productive. This is not just a simple replacement of the existing process, but a process involving comprehensive changes in business processes, corporate culture, and market strategies. Enterprises are transforming to manufacturing servitization and service-oriented manufacturing, changing the original business model and value system, better serving customers and improving their competitiveness [26]. The goal of digital transformation in the manufacturing industry is to promote business transformation, technological transformation, and organizational transformation of manufacturing enterprises. Among them, business transformation aims to promote the improvement of operational indicators through digital transformation of the entire value chain, including increasing revenue through digital means in sales and research and development, reducing costs through digital technology in procurement, manufacturing, and support departments, and optimizing cash flow through digital means in supply chain and capital management; technological transformation aims to build the industrial Internet of Things architecture and technology ecosystem required for enterprise digital transformation; organizational transformation aims to promote profound changes in the organizational structure, operational mechanisms, talent cultivation, and organizational culture of enterprises. There are three stages for enabling and reducing carbon in the manufacturing industry through digital transformation: the first stage is to reduce carbon through management, and reduce carbon through management platform or capacity adjustment. The second stage is to maintain the existing production methods and processes, increase carbon control and efficiency enhancing technologies or provide the public service digital platform to reduce carbon emissions. The third stage is the digital upgrading of the enterprise's core R&D and production process, reducing carbon through the intelligent production equipment and the evolution of business flow. The role of digital transformation mainly includes the following: first, enterprises using more intelligent digital equipment can alleviate the growth of energy consumption from the source to a certain extent, more scientifically predict and intervene the target energy demand, so as to prevent and reduce the generation of pollutants and waste of resources, accurately invest energy, optimize energy utilization, and effectively improve energy efficiency [27]. Second, enterprises can also predict the target energy demand through big data technology, reduce unnecessary pollutant emissions and resource waste, and improve the energy consumption and allocation efficiency of enterprises [28]. Third, in traditional production models, enterprises often rely heavily on human and material resources, leading to energy waste and environmental pollution. Through digital transformation, enterprises can gradually reduce production costs, improve efficiency, and help reduce environmental pollution [29]. Finally, the construction of infrastructure such as digital communication platforms is increasingly strengthening, laying a resource and knowledge foundation for manufacturing enterprises to carry out green technology innovation activities. The gradual improvement of digital infrastructure is conducive to increasing the frequency of innovation, cultivating high-end production factors, promoting the diffusion of technological innovation, and enhancing the possibility of new value creation under low resource consumption conditions [30]. In this context, this paper proposes the following first research hypothesis:

**Hypothesis 1.** *Manufacturing enterprises can promote the reduction in their carbon emissions through digital transformation.*

2.2.2. Indirect Impact of Digital Transformation on Low-Carbon Transformation of Enterprises

Green technological innovation is a technological innovation involving green products and green processes [31]. It not only brings economic benefits to enterprises and consumers, but also embodies the concept of green development [32], as an important driving force for the transformation and upgrading of economic structure, high-quality development, and sustainable development. Through digital transformation, enterprises can use digital technology to improve the market innovation environment, reduce innovation costs, and break the restrictions of time and space, so as to effectively improve innovation efficiency. First, digital technology can help accelerate the transmission of innovation information, improve the openness and transparency of the innovation ecosystem, and build a more inclusive and open innovation environment, thus promoting the progress of green technology innovation. Second, digital development enables core innovation elements such as knowledge and talents to circulate more quickly, improves the matching efficiency between innovation subjects and innovation elements, reduces search costs and coordination costs, and promotes the popularization and promotion of green technology.

Enterprises can transform traditional business processes and operational models into digital production and management models through digital transformation. Digital transformation can enable enterprises to monitor and manage resources more efficiently, optimize production processes, reduce energy consumption and waste generation, thereby promoting green technology innovation. The digital economy emphasizes open cooperation, and enterprises can collaborate with other enterprises, research institutions, and government departments to jointly promote green technology innovation. The digital economy provides new business models for enterprises, which can encourage them to provide more sustainable products and services, thereby promoting green technology innovation. In terms of energy conservation and emission reduction, green technology innovation optimizes the production process, scientifically allocates the use of production materials, and achieves the growth of enterprise profits and reduces energy waste and carbon emissions while keeping the total amount of production factors unchanged. In addition, green technology innovation can provide rich technological sources and research and development reserves for the development of the digital economy, provide the best products and services with minimal resource consumption, promote the reduction in unit carbon emission intensity, and promote the process of carbon reduction. It can also improve the marginal efficiency of digital production factors, maximize the substitution of fossil fuels with non-fossil fuels, and reduce carbon emission levels [33]. In addition, green technology innovation promotes the high-quality development of the industry by promoting the upgrading of the industrial structure, and produces greater social and economic benefits, which is conducive to the government to strengthen pollutant emission control, ecological environment protection and social welfare investment, and creates conditions for carbon emission reduction. Therefore, this paper puts forward the following assumptions:

**Hypothesis 2.** *Under the equal conditions of other conditions, digital transformation will promote green technology innovation through green technology innovation.*

## 3. Methods and Data

### *3.1. Extended STIRPAT Model*

The STIRPAT(Stochastic Impacts by Regression on Population, Affluence, and Technology) model is a variation of the IPAT model proposed by Ehrlich and Holdren [34]. With the deepening of research, people gradually found that the IPAT model has some problems, such as multicollinearity between variables and the inability to take into account the impact of human factors on the environment. To solve these problems, Dietz [35] proposed the STIRPAT model in 1997. The main difference between this model and the IPAT model is that the STIRPAT model introduces exponential variables, which can better deal with the influence of human factors. The general STIRPAT model is described as follows:

$$Iit = \alpha \times P_{it}^{\theta} \times A_{it}^{\gamma} \times T_{it}^{\eta} \times \varepsilon_{it} \quad (1)$$

where $I$ stands for environmental impact or environmental load. $P$, $A$, and $T$ are population size, regional per capita affluence, and overall regional technical level, respectively. $\theta$, $\gamma$, and $\eta$ represent the estimated parameters of $P$, $A$, and $T$. $i$, $t$, $\alpha$, and $\varepsilon$ are the region, time, constant term, and random error term, respectively. In order to eliminate the volatility in the time series and overcome its heteroscedasticity, logarithms of both ends of Equation (1) are taken as follows:

$$lnIit = ln\alpha + \theta lnP_{it} + \gamma lnA_{it} + \eta lnT_{it} + ln\varepsilon_{it} \quad (2)$$

The STIRPAT model's impact factors are extended to consider various influencing factors of carbon emission as comprehensively as possible. Specifically, environmental pressure ($I$) is expressed in terms of carbon emissions ($C$) of our manufacturing enterprises. The technical level ($T$) is expressed by the digital transformation level of manufacturing enterprises (*dig*). By reading literature and referring to previous studies of scholars, this paper selects five indicators of enterprise size (*size*), asset−liability ratio (*lev*), equity concentration (*cr*), equity liquidity (*lp*), and enterprise management level (*manage*) as control variables. The basic model is established as follows:

$$lnC_{it} = ln\alpha + \beta lndig_{it} + \theta lnsize_{it} + \lambda lnlev_{it} + \delta lncr_{it} + \gamma lnlp_{it} + \varphi lnmanage_{it} + ln\varepsilon_{it} \quad (3)$$

Among them, $lnC$, $lndig$, $lnsize$, $lnlev$, $lncr$, $lnlp$, $lnmanage$, respectively represent carbon emission, digital transformation level, enterprise scale, asset−liability ratio, equity concentration, equity liquidity, and enterprise management level. $\beta$, $\theta$, $\lambda$, $\delta$, $\gamma$, $\varphi$ are all estimated parameters. The other symbols have the same meaning as Equation (2).

### *3.2. Mediation Model*

In order to test the mechanism of digital transformation on low-carbon development, namely, whether green technology innovation is the mediator of the two, this paper sets a mediating model between digital transformation and carbon emission, as shown in Equations (4)–(6).

$$lnC_{it} = alndig_{it} + \sum_{k=1}^{n} \theta_k lnX_{it} + e_1 \quad (4)$$

$$lngti_{it} = blndig_{it} + \sum_{k=1}^{n} \theta_k lnX_{it} + e_2 \quad (5)$$

$$lnC_{it} = clndig_{it} + dlngti_{it} + \sum_{k=1}^{n} \theta_k lnX_{it} + e_3 \quad (6)$$

If $c$ and $d$ are significant, this indicates that there is an intermediary effect; otherwise, there is no intermediary effect.

### *3.3. Panel Threshold-STIRPAT Model*

Hansen [36] first proposed a threshold model to describe the correlation of jump or structural fracture between different variables. This study hopes to verify the nonlinear characteristics of the application of enterprise digital technology on the reduction in carbon dioxide emissions from the perspective of green technology innovation. We build a panel threshold model and the model is as follows:

$$lnC_{it} = ln\alpha + \beta_1 lndig_{it} I\cdot(lngti_{it} \le \gamma) + \beta_2 lndig_{it} I\cdot(lngti_{it} > \gamma) + \sum_{m=1}^{n} \theta_m lnX_{it} + ln\varepsilon_{it} \quad (7)$$

$\ln X_{it}$ represents a series of control variables, consisting of $\ln$ size, $\ln$ lev, $\ln$ cr, $\ln$ lp, $\ln$ manage. $\gamma$ is a threshold. $\beta_1$, $\beta_2$, and $\theta_m$ are estimated parameters. The other symbols have the same meaning as Equation (3).

### *3.4. Variables and Data*

#### 3.4.1. Explained Variable

When assessing the carbon emission level of enterprises, China's current legal system does not require enterprises to disclose carbon emission information. Therefore, we found that only a few enterprises would voluntarily disclose carbon emission data in their annual reports. Due to the limited availability of enterprise data, we refer to the research methods of Shen et al. [37]. This method calculates carbon emissions according to the operating costs of enterprises. The specific calculation method is shown in Equation (8).

$$\mathrm{CO_2} Emissions = \frac{Operating\ Costs\ of\ the\ Enterprise}{Operating\ Costs\ of\ the\ Industry} \times Industrial\ CO_2\ Emissions \quad (8)$$

#### 3.4.2. Explanatory Variable

With the wide application of text big data in the field of economy and finance, literature research in recent years has begun to use text analysis to describe the degree of digitalization of enterprises. Compared with other methods, text analysis can comprehensively reflect the degree of digital transformation of micro enterprises, and has a high reference value [38]. Based on the practice of Wu et al. [39], using semantic expressions of national policies related to the digital economy and text analysis, we construct digital transformation indicators reflecting China's listed manufacturing enterprises.

#### 3.4.3. Mediating Variable and Threshold Variable

This paper uses the research methods of Qi et al. [40] and Li and Xiao [41] for reference. This article uses the number of green patent applications by enterprises as a proxy variable for their level of green innovation. This method can accurately reflect the level of green technology innovation of enterprises, and is of great significance for evaluating the relationship between digital transformation and carbon emissions.

#### 3.4.4. Control Variable

Based on previous studies, this paper selects variables related to the corporate characteristics for control. Their impact on enterprise carbon emission levels may have the following reasons: The first is the enterprise scale (size), which refers to the total assets of the enterprise in that year. The larger the enterprise, the greater the carbon emissions it produces. The second is the asset−liability ratio (lev), namely, the proportion of the total liabilities of the enterprise in its total assets. Higher debt may limit a company's contribution to carbon reduction. In addition, ownership concentration (cr) represents the shareholding ratio of the largest shareholder. It reflects the concentration of power structure within the company, which may have a significant impact on the business strategy, management mode, and environmental responsibility of the enterprise. Equity liquidity (lq) represents the shareholding ratio of the top 10 shareholders. It reflects the transfer and reallocation of interests among shareholders, and may also directly affect the strategic direction and business priorities of enterprises. Finally, the level of enterprise management (manage), which is related to the ratio between management expenses and main business income. When formulating development strategies and resource allocation plans, enterprises usually consider the impact of environmental factors. The difference in management expense rates among different enterprises reflects their different characteristics in management and operation. The selection of these control variables can better help us accurately estimate the real impact of the variables of concern.

The above-mentioned main variables are defined in Table 1.

**Table 1.** Definition and measurement of variables.

| | Symbol | Variable | Measurement |
|---|---|---|---|
| Explained variable | C | carbon emission | Carbon emissions per unit of operating income |
| Explanatory variable | dig | digital transformation | Digital word frequency in enterprise annual reports |
| Mediating variable and threshold variable | gti | green technology innovation | The count of green invention patents, increased by one |
| Control variable | size | enterprise scale | The total assets of the enterprise in that year |
| | lev | Asset−liability ratio | Total business liabilities/total assets |
| | cr | ownership concentration | Shareholding ratio of the largest shareholder |
| | lp | Equity liquidity | Shareholding ratio of the top 10 shareholders |
| | manage | enterprise management | Management expense/main business income |

### *3.5. Data Sources*

Considering the relatively large sample size and long listing time of manufacturing listed companies, as well as the abundant and complete data available in relevant annual reports, this article selects manufacturing listed companies on the Shanghai and Shenzhen A-shares from 2013 to 2021 as the research object and conducts the following data processing steps: first, the samples with special processing such as ST and PT are excluded; second, the samples with serious missing variables are eliminated; third, discontinuous variables are treated with Winsor tails on both sides reduced by 1%. After processing, this paper finally sorted out 9194 groups of sample data of 1900 enterprises. The data used in this paper at the enterprise level mainly come from the CSMAR database, which involves downloading and processing annual report data from the official websites of the Shenzhen Stock Exchange and Shanghai Stock Exchange. Industry and regional level data are sourced from the China Industrial Statistical Yearbook, China Statistical Yearbook, and China Regional Statistical Yearbook.

We estimate corporate carbon emissions using industry carbon emissions based on the proportion of operating costs. The industry's carbon emissions are taken from the China Carbon Emission Accounts and Datasets (CEADS). The cost data of the industry's main business are taken from the China Industrial Statistical Yearbook. In measuring enterprise digital transformation, we construct a digital terminology dictionary for enterprises, and use Python word segmentation processing technology and manual recognition methods to summarize and organize keywords related to digital transformation; second, we match the text content in the "Management Discussion and Analysis" (MD&A) section of the annual reports of listed companies from 2013 to 2021 with the keywords in the digital transformation terminology dictionary, count the frequency of relevant words, and construct the listed company annual variables; finally, we construct digital transformation indicators. The larger the total number of digitalization related vocabulary in the MD&A annual report of a company, the higher its level of digital transformation. To measure the level of green technology innovation in enterprises, we obtain the patent classification number information of invention patents and utility model patents of listed companies from the China Research Data Service Platform (CNRDS), and then match it with the "International Patent Classification Green List" published by the World Intellectual Property Organization (WIPO). Based on the association results, the patents of listed companies are divided into two categories: green patents (green invention patents and green utility model patents) and non-green patents (non-green invention patents and non-green utility model patents). The data processing software used was Stata 16.0.

According to Table 2, the explanatory variables range from 0 to 4.431, with an average of 1.197, indicating that there are significant differences in the degree of digital transformation between different enterprises. In terms of green technology innovation, the variable range is 0~3.912, with an average value of 0.478, indicating that enterprises' green technology is generally in the primary stage, and there is a gap in the promotion effect of green technology among different enterprises. From the perspective of the explained variable, the sample value is between 0.100 and 9.066, with an average of 2.859, indicating that China's manufacturing enterprises still have a large amount of room for emission reduction.

**Table 2.** Descriptive statistics of variables.

| Variable | Mean | Standard Deviation | Minimum | Maximum | Observations |
|---|---|---|---|---|---|
| lnC | 2.859 | 2.192 | 0.100 | 9.066 | 9194 |
| lndig | 1.177 | 1.200 | 0.000 | 4.431 | 9194 |
| lngti | 0.478 | 0.888 | 0.000 | 3.912 | 9194 |
| lnsize | 22.130 | 1.186 | 20.014 | 25.690 | 9172 |
| lnlev | −1.065 | 0.595 | −2.898 | −0.080 | 9172 |
| lncr | −1.188 | 0.444 | −2.410 | −0.339 | 9194 |
| lnlp | −0.589 | 0.276 | −1.455 | −0.125 | 9194 |
| lnmanage | −2.643 | 0.665 | −4.540 | −0.987 | 9194 |

## 4. Results

### *4.1. Impact of Digital Transformation on Carbon Emissions*

Using Formula (3), we build a panel regression model to explore the relationship between the variables, so as to prove that the digital transformation of manufacturing industry does have a significant impact on carbon emissions. Combined with the Hausman test results, chi2 (6) = 504.50 and $p$ = 0.0000, the fixed effect was selected for analysis. According to the results of model (1) in Table 3, at the 1% level, every 1% increase in the degree of digital transformation will significantly reduce carbon emissions by 0.103%. In addition, the size of an enterprise reflects its business volume and scope of activities. The larger the size of an enterprise, the greater the amount of carbon dioxide it emits into the ecological environment. The higher the asset−liability ratio of enterprises, the greater the constraints and pressures on capital and resources, and the level of carbon emissions of enterprises will rise accordingly. Therefore, enterprises may pay more attention to short-term economic benefits; therefore, they prefer to adopt high energy consumption and high emission production methods in the production process to reduce costs. At the same time, the high asset−liability ratio will also affect the business strategy and investment decisions of enterprises, so that enterprises in the field of environmental protection investment and attention are relatively less. The largest shareholder has a strong voice in the enterprise, which may mean that other major shareholders or minority shareholders have a relatively weak influence on enterprise decision-making. This may lead to the lack of sufficient checks and balances and supervision in the carbon emission decisions of enterprises, increasing the possibility of high carbon emissions of enterprises. The higher equity liquidity reflects the instability of the ownership structure of manufacturing enterprises and the short-term investment behavior of investors. Since investors hold enterprises for a short time, they may pay more attention to the short-term performance of enterprises, and managers ignore the application of green production mode. A higher overhead rate may mean that a company has invested more resources in management, including human, material and financial resources, to improve its operational efficiency and reduce the inappropriate use of resources through refined management.

### *4.2. Mediating Effect of Green Technology Innovation*

We tested model (4), model (5), and model (6) using the Hausmann test. The statistical values of Chi2 (6) in the model were 504.50, 127.07, and 354.95, respectively, with a $p$ value of 0.0000. These results show that models (4) to (6) are more suitable for fixed effects.

See Table 4 for the mediation effect analysis results. According to model (4), for every 1% increase in the degree of digital transformation of enterprises, their carbon emissions will be reduced by 0.103%. Model (5) points out that the level of green technology innovation will increase by 0.023% for every 1% increase in the degree of enterprise digital transformation. The results of model (6) show that the regression coefficients of enterprise digital transformation and green technology innovation are significant at the level of 1%, which are −0.103 and −0.033, respectively. The existence of mediating effect is explained.

**Table 3.** Regression results of benchmark model and their robustness tests.

| Variable | Model (1) FE | Model (2) FE | Model (3) 2SLS |
|---|---|---|---|
| lndig | −0.103 ***<br>(−12.58) | −0.187 ***<br>(−12.29) | −1.171 ***<br>(−17.58) |
| lnsize | 0.198 ***<br>(12.31) | 0.181 ***<br>(11.45) | 0.811 ***<br>(17.07) |
| lnlev | 0.125 ***<br>(6.10) | 0.128 ***<br>(6.18) | 0.035<br>(0.94) |
| lncr | 0.310 ***<br>(8.65) | 0.320 ***<br>(8.87) | 0.048<br>(−0.69) |
| lnlp | 0.197 ***<br>(4.03) | 0.192 ***<br>(3.88) | 0.192<br>(−0.07) |
| lnmanage | −0.138 ***<br>(−8.86) | −0.136 ***<br>(−8.67) | −0.283 ***<br>(−9.50) |
| Constant | −1.139 ***<br>(−3.31) | −0.727 **<br>(−2.15) | −14.481 **<br>(−14.09) |
| Obs | 9172 | 9072 | 9161 |
| R-sq | 0.083 | 0.078 | 0.078 |
| Instrumental variable | – | – | lndig_1 |
| F statistics | 58.36 *** | 55.43 *** | 17.08 *** |

Note: The t or z values are in parentheses; ** $p < 0.05$, *** $p < 0.01$.

**Table 4.** Regression results of mediating effect.

| Variable | DEPVAR = lnC | DEPVAR = lngti | DEPVAR = lnC | DEPVAR = lngti_1 | DEPVAR = lnC |
|---|---|---|---|---|---|
| | Model (4) | Model (5) | Model (6) | Model (7) | Model (8) |
| lndig | −0.103 ***<br>(−12.58) | 0.023 ***<br>(2.67) | −0.103 ***<br>(−12.49) | 0.018 ***<br>(2.57) | −0.103 ***<br>(−12.49) |
| lngti | – | – | −0.033 ***<br>(−2.94) | – | – |
| lngti_1 | – | – | – | – | −0.043 ***<br>(−3.15) |
| lnsize | 0.198 ***<br>(12.31) | 0.099 ***<br>(12.31) | 0.201 ***<br>(12.49) | 0.089 ***<br>(6.46) | 0.201 ***<br>(12.52) |
| lnlev | 0.125 ***<br>(6.10) | −0.036 *<br>(−1.68) | 0.124 ***<br>(6.05) | −0.145<br>(−0.82) | 0.125 ***<br>(6.08) |
| lncr | 0.310 ***<br>(8.65) | −0.30<br>(−0.78) | 0.309 ***<br>(8.65) | −0.474<br>(−1.54) | 0.308 ***<br>(8.59) |
| lnlp | 0.197 ***<br>(4.03) | −0.137 ***<br>(−2.66) | 0.192 ***<br>(3.94) | −0.060<br>(−1.43) | 0.194 ***<br>(3.98) |
| lnmanage | −0.138 ***<br>(−8.86) | −0.105 ***<br>(−6.39) | −0.142 ***<br>(−9.06) | −0.036 ***<br>(−2.71) | −0.140 ***<br>(−8.96) |
| Constant | −1.139 ***<br>(−3.31) | −2.161 ***<br>(−5.98) | −1.210 ***<br>(−3.51) | −1.822 ***<br>(−6.16) | −1.217 ***<br>(−3.53) |
| Obs | 9172 | 9172 | 9172 | 9172 | 9172 |
| R-sq | 0.083 | 0.026 | 0.080 | 0.019 | 0.080 |
| F statistics | 58.36 *** | 10.36 *** | 57.87 *** | 11.24 *** | 57.82 *** |

Note: The t or z values are in parentheses; * $p < 0.1$, *** $p < 0.01$.

### *4.3. Threshold Effect Analysis of Green Technology Innovation*

We choose green technology innovation as the threshold variable. According to the results in Table 5, we can know that there is a single threshold effect.

**Table 5.** Results of the threshold effect significance test.

| Models | Threshold Estimates | F Value | *p* Value | 1% | 5% | 10% | 95% Confidence Interval |
|---|---|---|---|---|---|---|---|
| Single-threshold | 0.693 | 24.13 | 0.000 | 14.010 | 8.806 | 7.278 | [0.000, 1.099] |
| Double-threshold | 1.792 | 5.42 | 0.216 | 21.063 | 10.600 | 7.507 | [0.805, 1.946] |

Notes: bootstrap = 500, seed = 1,234,567.

The analysis results of threshold effect can be seen in Table 6. When the level of green technology innovation is lower than 0.693, the carbon emissions of enterprises will be significantly reduced by 0.097% for every 1% increase in the degree of digitalization. This shows that enterprises may lack sufficient technical means to effectively use digital transformation to reduce carbon emissions. Enterprises tend to invest resources to expand production and reduce costs, while ignoring environmental protection and sustainable development. When the level of green technology innovation of enterprises is greater than 0.693, carbon emissions will be reduced by 0.108% for every 1% increase in the degree of digitalization of enterprises, both of which are significant at the 99% confidence level. This shows that when the threshold is reached, enterprises begin to pay attention to environmental protection and sustainable development, and invest more resources in digital transformation and green development to reduce carbon emissions. When the threshold value is exceeded, its effect on reducing carbon emissions is significantly enhanced.

**Table 6.** Panel threshold regression results and their robustness tests.

| Variable | Model (10) | Variable | Model (11) |
|---|---|---|---|
| lndig(lngti $\leq$ 0.693) | −0.097 ***<br>(−7.85) | lndig(lngti $\leq$ 0.693) | −0.100 ***<br>(−7.61) |
| lndig(lngti > 0.693) | −0.108 ***<br>(−8.28) | lndig(lngti > 0.693) | −0.108 ***<br>(−8.12) |
| lnsize | 0.240 ***<br>(10.65) | lnsize | 0.261 ***<br>(10.81) |
| lnlev | 0.103 ***<br>(3.08) | lnlev | 0.083 **<br>(2.33) |
| lncr | 0.387 ***<br>(7.66) | lncr | 0.352 ***<br>(6.53) |
| lnlp | 0.225 ***<br>(3.17) | lnlp | 0.236 ***<br>(3.14) |
| lnmanage | −0.122 ***<br>(−5.36) | lnmanage | −0.089 ***<br>(−3.73) |
| Constant | −1.946 ***<br>(−3.99) | Constant | −2.362 ***<br>(0.522) |
| Obs | 9172 | Obs | 9172 |
| R-sq | 0.092 | R-sq | 0.084 |
| F statistics | 70.37 *** | F statistics | 70.13 *** |

Note: t statistics in parentheses, ** $p < 0.05$, *** $p < 0.01$, bootstrap = 500, seed = 1,234,567.

### *4.4. Heterogeneity Analysis*

According to the results of Table 7, we draw the following conclusions. First, both can effectively reduce carbon emissions of enterprises by using digital technology. Second, the emission reduction effect of state-owned enterprises is more obvious. The main reasons for this conclusion may be as follows: First, from the perspective of input cost and transformation difficulty, state-owned enterprises have advantages in capital, technology and resources, etc., and are easier to invest in digital transformation, and achieve emission reduction by optimizing production processes and improving energy efficiency.

Non-state-owned enterprises may face capital, technology and resource constraints, and the transition is relatively difficult; therefore, the emission reduction effect may be relatively weak. Second, from the perspective of industrial structure, state-owned enterprises usually have a relatively complete industrial chain and a high degree of industrial concentration. The application of digital technology improves their production efficiency, makes resource allocation more reasonable, and reduces environmental pollution. However, non-state-owned enterprises may have problems such as single industrial structure and imperfect industrial chain, and the impact of digital transformation on their emission reduction effect may be relatively small. Third, considering the situation of energy consumption, most state-owned enterprises belong to the heavy industry with large energy consumption and carbon emissions. Through digital transformation, its energy consumption and carbon emission structure can be improved, so as to improve energy efficiency and enhance emission reduction effect. However, non-state-owned enterprises are mainly concentrated in the field of light industry, and their energy consumption and carbon emissions are relatively low. Therefore, the impact on non-state-owned enterprises may be relatively weak.

**Table 7.** Heterogeneity test.

| Variable | State-Owned | Variable | Non-State-Owned |
|---|---|---|---|
| lndig | −0.172 *** (−10.97) | lndig | −0.059 *** (−6.41) |
| lnsize | 0.331 *** (11.11) | lnsize | 0.073 *** (3.84) |
| lnlev | 0.295 *** (6.11) | lnlev | 0.083 ** (4.56) |
| lncr | 0.341 *** (−5.59) | lncr | 0.236 *** (5.63) |
| lnlp | 0.224 ** (2.54) | lnlp | 0.167 *** (2.88) |
| lnmanage | −0.154 *** (−5.59) | lnmanage | −0.103 *** (−5.60) |
| Constant | −3.181 *** (−4.73) | Constant | 1.117 *** (2.81) |
| Obs | 2976 | Obs | 6196 |
| R-sq | 0.153 | R-sq | 0.037 |
| F statistics | 70.89 *** | F statistics | 54.15 *** |

Note: t statistics in parentheses, ** $p < 0.05$, *** $p < 0.01$.

### *4.5. Robustness Test*

#### 4.5.1. Robustness Test of the Benchmark Model

Previous research [42,43] pointed out that the estimation method of alternative indicators or changes is a common means of robustness testing. Referring to the research of Yuan et al. [44], a new method is used to measure the degree of digital transformation. In addition, considering that there may be endogenous problems, this paper uses the two-stage least squares (2SLS) instrumental variable method to deal with the possible endogenous problems in the empirical research. Based on the practice of Xiao et al. [45], by observing the average digitization degree of other manufacturing enterprises in the same year except for the sample, this paper uses it as a tool variable to improve the accuracy of the results, and fully overcomes its endogeneity. In the first stage, the model regression tests the correlation between the digitalization degree of the same industry and the digitalization degree of the enterprise. The study found that the average digitalization degree of the same industry in the same year had a great correlation with the digitalization of enterprises, but there was no direct logical correlation with the explained variables, indicating that the selected tool variables performed well. In the results of the second stage regression model, the difference between the values of model (3) and model (1) is very small in Table 3, and there is still a significant emission reduction effect.

#### 4.5.2. Robustness Test of the Mediating Effect

In order to make the result more reliable, we verified whether the mediating effect still exists by observing the sum of the number of green patents granted by enterprises in that year (lngti_1). According to the results of model (7) and model (8) in Table 4, the results are still good, and the role of mediator still exists.

#### 4.5.3. Robustness Test of the Threshold Effect

In order to verify its robustness, the total number of green patents authorized by the enterprise in the current year (lngti_1) is selected as an alternative variable. Model (11) in Table 6 reports the re-estimated regression results. The coefficient changes a little, and there is no significant difference. Therefore, the results of panel threshold regression are reliable.

## 5. Discussion

This study not only enriches the exploration of the development path of the future manufacturing industry, but also provides reference for the green development of other industries.

First of all, we used the relevant data of Chinese listed manufacturing enterprises from 2013 to 2021. Through the analysis of the benchmark model, the results show that the digital transformation has significantly reduced the carbon dioxide emissions generated by enterprises in production and business activities. The H1 hypothesis is well verified. The results are consistent with the conclusions of Si et al. [46]. This discovery once again confirms the view advocated by Xu et al., namely, through the digital transformation strategy, ecological management innovation can be optimized, so as to enhance the ability of sustainable development [47]. The possible reasons are, first of all, that enterprises update technology and equipment, optimize production processes, and improve production efficiency [48]. Second, enterprises optimize the energy structure, manage and control energy use more accurately, improve energy utilization efficiency, and reduce unnecessary energy waste [49]. In addition, enterprises use advanced technology to promote the reform of enterprise management and business model, solve the problem of sustainable development, and realize the harmonious coexistence of economy and ecology [50]. Currently, in order to achieve the transformation of new and old industrial kinetic energy towards digitization, networking, and intelligence, it is not enough to only achieve automation of machinery and equipment. It is also necessary to use digital twins and other methods to enable machines to accurately perceive, control, collaborate, arrange automatically, and make autonomous decisions. Enterprises can make a bigger impact by achieving their sustainable development goals.

Second, the mediating effect of green technology innovation exists and plays a role that cannot be ignored. The digital transformation of enterprises achieves the emission reduction goal through green technology innovation [38]. The mechanism of its action is further studied. In the process of digital development, enterprises integrate social responsibility into their own operation and development, improve information transparency, reduce financing pressure, and increase R&D efforts [51]. Moreover, in the enterprise green technology innovation activities, enterprise digitalization exerts the knowledge sharing effect and resource effect, and significantly improves the production efficiency of enterprises [46]. Intelligent technology can enable enterprises to respond to market changes faster and give good strategies to improve service levels. In addition, digital transformation provides a new starting point for enterprises' green technology innovation, and the digital supply chain management system also provides a strong guarantee for enterprises' comprehensive improvement in green technology innovation.

In addition, regression through the panel threshold model shows that the enterprise digital transformation and carbon emissions have a significant negative nonlinear relationship of "diminishing marginal effect", and the Hypothesis 2 is well verified. By integrating these three key elements, this paper emphasizes the important role of green technology innovation. It breaks the one sidedness of previous studies and enriches the situational research on how the digital transformation of enterprises affects carbon emission reduction.

From the perspective of reasons, first, the level of digital technology is low and has not yet formed a large-scale development trend. It is difficult to obtain and transmit green knowledge, technology, and other information, which is not conducive to green technology innovation. With the deepening of the transformation, the construction of digital infrastructure is more perfect, and there are more channels to obtain green technology and knowledge, which is conducive to the improvement of the level of green technology innovation. When it reaches a certain level, the channels for enterprises to acquire knowledge, information, and various resources tend to be improved, and the scale effect is more and more significant. In this process, the carbon emission reduction effect shows a gradual upward trend. Second, under the guidance of green technology innovation, enterprises use information technology to transform to a more environmentally friendly and efficient production mode, thereby reducing energy consumption and carbon emissions. Third, with the progress of green technology, enterprises gradually improve resource utilization efficiency and optimize energy consumption structure in the process of digital transformation, so as to reduce their carbon footprint.

There are some deficiencies worth further discussion in this paper. First of all, this paper only analyzes China's manufacturing industry. There may be different conclusions for other sectors, and it is still worth exploring in the future. In the future research, we should horizontally compare the carbon emission reduction models of enterprises in different industries to enrich the content of related fields. Second, the digital transformation of enterprises and the development of carbon emissions are affected by the national economic development environment, government policy guidance, industrial structure and other factors, which cannot be ignored. However, this paper does not involve the specific role of the macro policy environment on the relationship between the two. Finally, we only use the data of listed companies, not non-listed companies, which may affect the accuracy of the study.

## 6. Conclusions and Recommendations

### 6.1. Conclusions

This paper starts with the optimization of resource allocation brought by digital transformation, and demonstrates in detail the theoretical mechanism of enterprise digital transformation to promote carbon emission reduction from the perspective of green technology progress. Based on the panel data of Chinese manufacturing enterprises, this paper uses fixed effect model, intermediary effect model, and panel threshold model to make a multi-dimensional empirical test of the impact of digital transformation on carbon emissions. The study found the following: first, digital transformation has an important role in promoting the reduction in carbon emissions, and after a series of robustness tests, this trend is still applicable. Second, the mechanism test shows that green technology innovation plays a positive intermediary effect in the impact of digital transformation on low-carbon development of enterprises. Green technology innovation has become an important way for digital technology innovation to promote carbon emission reduction. Third, the threshold effect test found that when taking green technology innovation as the threshold variable, digital transformation has a significant single threshold effect on the low-carbon development of enterprises. When the explained variable is enterprise carbon emissions, and when the level of green technology innovation is lower than 0.693, the marginal impact is −0.097. When green technology innovation exceeds this threshold, the marginal impact will reach −0.108. Fourth, heterogeneity analysis shows that among enterprises of different nature, the impact of digital transformation on carbon emission reduction in state-owned enterprises is more significant.

### 6.2. Recommendations

First, actively building high-quality network relationships and improving the external ecosystem of digital transformation. Small- and medium-sized enterprises should actively respond to and deeply participate in the "cloud based digital empowerment" action, strengthen communication and interaction with the government, customers, and suppliers, timely obtain innovative resources and key information for digital transformation, and accelerate digital innovation of products and services; continuously deepen cooperation with leading enterprises in the industry, such as leading enterprises, large platform enterprises, and digital transformation service enterprises, and work together through various paths such as government market collaboration, upstream and downstream integration of the industrial chain, and leading enterprises to promote high-quality digital transformation. Relevant departments should actively take economic measures such as capital subsidies, tax cuts, and loan support to boost enterprise confidence and guide enterprises to accelerate the strategic layout of advanced intelligent manufacturing industry. We will improve our ability to support industrial development, accelerate the system construction of intelligent manufacturing, and realize the transformation from "made in China" to "intelligent manufacturing in China". Through intelligent manufacturing, quality management can be strengthened. We should make Chinese products go global while meeting the internal circulation, especially to countries along the "belt and road". Therefore, we should explore the market through intelligent manufacturing.

Second, strengthen the promotion of digital transformation theory and technology, as well as excellent demonstration cases. Although many manufacturing companies currently have some understanding of digital transformation, they are more limited to operational digital transformation such as office automation, and their understanding of the digitalization of the entire organizational system is not deep enough. It is suggested to organize institutions such as universities and research institutes to provide more theoretical guidance to enterprises, including not only the basic theory of digital transformation throughout the entire production, operation, sales and other processes of the enterprise, but also to enable enterprises to learn and think about how to carry out digital transformation and upgrading in various stages based on their own industry characteristics. At the same time, we can also increase the promotion of benchmark intelligent factory cases, such as regularly organizing enterprises to visit and learn from excellent demonstration bases of intelligent factories, and organizing digital transformation forums and learning activities regularly by chambers of commerce, industry associations, etc.

Third, attach importance to green technology innovation, increase investment in green technology research and development, and improve the overall innovation ability. Additionally, establish an innovation exchange platform, promote the cooperation and exchange of relevant departments such as production, education and scientific research, jointly solve development problems, promote the intelligent transformation of green technology, promote digital green production platforms such as the green product design system, green manufacturing decision-making system, and green product recycling system, and promote the manufacturing industry to achieve better quality and efficiency. Innovative design is also an important way to drive green technology innovation. The realization of innovative design is mainly reflected in three aspects: material, process, and design. Compared with general design, innovative design emphasizes the essential changes with the original product in one or more innovative elements such as new principles, new functions, new mechanisms, new structures, new appearances, new materials or new processes. It fully embodies the green characteristics, can meet the new needs of users or the market, and win in the market competition.

Fourth, continue to improve the whole value chain of the enterprise under the guidance of high-quality development. Enterprises can introduce a complete lean digital management system to make up for their shortcomings in manufacturing, procurement, research and development, logistics supply chain, strategy and other aspects through lean improvement, so as to enhance their comprehensive competitiveness. Through the improvement of process, the past labor-intensive process will be transformed into an automated, digital and intelligent process, which requires the reconstruction, reorganization, optimization, and improvement of the original process composition to make the process more optimized and meet the needs of the development of manufacturing industry. Enterprises should formulate targeted strategies, realize the integration of industrialization and informatization, and make the development of enterprises more stable and sustainable.

Finally, we should speed up the training of digital interdisciplinary talents. We should promote the top leaders of enterprises to change their ideas, strengthen the training of digital transformation talents, and cultivate high-quality digital transformation talents according to different needs. We can provide technical guidance for the digital transformation of enterprises and cultivate more excellent talents for the construction of the manufacturing industry by carrying out investigations at home and abroad and strengthening cooperative training. It is necessary to establish a dynamic monitoring mechanism for global high-level talents in the "double carbon" key fields, so as to provide decision-making reference for the targeted introduction and independent cultivation of "double carbon" scientific and technological talents;China will strengthen the training of interdisciplinary scientific and technological talents who meet the "double carbon" standard and expand China's influence on the international standard platform.

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## References

1. Shi, Y.; Yuan, X.; Tang, Y.; Li, Y.; Wang, Q.; Ma, Q.; Zuo, J.; Liu, H. Localized regional life cycle model research for the impacts of carbon dioxide on human health and ecosystem. *Sustain. Prod. Consum.* **2022**, *29*, 36–45. [CrossRef]
2. Xiao, H.; Zhou, Y.; Zhang, N.; Wang, D.; Shan, Y.; Ren, J. $CO_2$ emission reduction potential in China from combined effects of structural adjustment of economy and efficiency improvement. *Resour. Conserv. Recycl.* **2021**, *174*, 105760. [CrossRef]
3. Jiang, L.; Zhou, H.; He, S. Does energy efficiency increase at the expense of output performance: Evidence from manufacturing firms in Jiangsu province, China. *Energy* **2021**, *220*, 119704. [CrossRef]
4. Miao, C.; Fang, D.; Sun, L.; Luo, Q. Natural resources utilization efficiency under the influence of green technological innovation. *Resour. Conserv. Recycl.* **2017**, *126*, 153–161. [CrossRef]
5. Yin, X.; Wang, Z.; Chen, J.; Li, J. Digital Transformation and Manufacturing Firms' Green Technological Innovation—A Study based on Big Data Mining. *J. Beijing Inst. Technol.* **2023**, *25*, 159–170.
6. Tang, C.; Xu, Y.; Hao, Y.; Wu, H.; Xue, Y. What is the role of telecommunications infrastructure construction in green technology innovation? A firm-level analysis for China. *Energy Econ.* **2021**, *103*, 105576. [CrossRef]
7. Xie, J. Analysis on the digital transformation index system of enterprise's low carbon business performance based on AHP-DEA. *Front. Energy Res.* **2023**, *10*, 1094440. [CrossRef]
8. Gao, J.; Xu, N.; Zhou, J. Does digital transformation contribute to corporate carbon emissions reduction? Empirical evidence from China. *Sustainability* **2023**, *15*, 13414. [CrossRef]
9. Lu, L.; Liu, P.; Yu, J.; Shi, X. Digital inclusive finance and energy transition towards carbon neutrality: Evidence from Chinese firms. *Energy Econ.* **2023**, *127*, 107059. [CrossRef]
10. Shang, Y.; Raza, S.A.; Huo, Z.; Shahzad, U.; Zhao, X. Does enterprise digital transformation contribute to the carbon emission reduction? Micro-level evidence from China. *Int. Rev. Econ. Financ.* **2023**, *86*, 1–13. [CrossRef]
11. Usai, A.; Fiano, F.; Petruzzelli, A.M.; Paoloni, P.; Briamonte, M.F.; Orlando, B. Unveiling the impact of the adoption of digital technologies on firms' innovation performance. *J. Bus. Res.* **2021**, *133*, 327–336. [CrossRef]
12. Zhang, R.; Fu, W.; Kuang, Y. Can digital economy promote energy conservation and emission reduction in heavily polluting enterprises? Empirical evidence from China. *Int. J. Environ. Res. Public Health* **2022**, *19*, 9812. [CrossRef] [PubMed]
13. Zhou, X.; Zhou, D.; Zhao, Z.; Wang, Q. A framework to analyze carbon impacts of digital economy: The case of China. *Sustain. Prod. Consum.* **2022**, *31*, 357–369. [CrossRef]

14. Li, Z.; Wang, J. The dynamic impact of digital economy on carbon emission reduction: Evidence city-level empirical data in China. *J. Clean. Prod.* **2022**, *351*, 131570. [CrossRef]
15. Yang, G.; Wang, F.; Deng, F.; Xiang, X. Impact of digital transformation on enterprise carbon intensity: The Moderating Role of Digital Information Resources. *Int. J. Environ. Res. Public Health* **2023**, *20*, 2178. [CrossRef] [PubMed]
16. Nazam, M.; Hashim, M.; Nută, F.M.; Yao, L.; Zia, M.A.; Malik, M.Y.; Usman, M.; Dimen, L. Devising a mechanism for analyzing the barriers of block chain adoption in the textile supply chain: A sustainable business perspective. *Sustainability* **2022**, *14*, 16159. [CrossRef]
17. Huang, J.; Liu, Q.; Cai, X.; Hao, Y.; Lei, H. The effect of technological factors on China's carbon intensity: New evidence from a panel threshold model. *Energy Policy* **2018**, *115*, 32–42. [CrossRef]
18. Wang, J.; Wang, S.; Li, S.; Cai, Q.; Gao, S. Evaluating the energy-environment efficiency and its determinants in Guangdong using a slack-based measure with environmental undesirable outputs and panel data model. *Sci. Total Environ.* **2019**, *663*, 878–888. [CrossRef] [PubMed]
19. Jain, A. How knowledge loss and network-structure jointly determine R&D productivity in the biotechnology industry. *Technovation* **2023**, *119*, 102607.
20. Song, W.; Yu, H. Green innovation strategy and green innovation: The roles of green creativity and green organizational identity. *Corp. Soc. Responsib. Environ. Manag.* **2018**, *25*, 135–150. [CrossRef]
21. Bouncken, R.B.; Ratzmann, M.; Kraus, S. Anti-aging: How innovation is shaped by firm age and mutual knowledge creation in an alliance. *J. Bus. Res.* **2021**, *137*, 422–429. [CrossRef]
22. Guerra, J.M.M.; Danvila-del-Valle, I.; Méndez-Suárez, M. The impact of digital transformation on talent management. *Technol. Forecast. Soc. Chang.* **2023**, *188*, 122291. [CrossRef]
23. Zhang, G.; Gao, Y.; Li, G. Research on Digital Transformation and Green Technology Innovation—Evidence from China's Listed Manufacturing Enterprises. *Sustainability* **2023**, *15*, 6425. [CrossRef]
24. Ning, J.; Yin, Q.; Yan, A. How does the digital economy promote green technology innovation by manufacturing enterprises? Evidence from China. *Front. Environ. Sci.* **2022**, *10*, 967588. [CrossRef]
25. Annarelli, A.; Battistella, C.; Nonino, F.; Parida, V.; Pessot, E. Literature review on digitalization capabilities: Co-citation analysis of antecedents, conceptualization and consequences. *Technol. Forecast. Soc. Chang.* **2021**, *166*, 120635. [CrossRef]
26. Kohtamäki, M.; Parida, V.; Oghazi, P.; Gebauer, H.; Baines, T. Digital servitization business models in ecosystems: A theory of the firm. *J. Bus. Res.* **2019**, *104*, 380–392. [CrossRef]
27. Zhang, S.; Wei, X. Does information and communication technology reduce enterprise's energy consumption? evidence from Chinese manufacturing enterprises survey. *China Ind. Econ.* **2019**, *2*, 155–173.
28. Goralski, M.A.; Tan, T.K. Artificial intelligence and sustainable development. *Int. J. Manag. Educ.* **2020**, *18*, 100330. [CrossRef]
29. Zhao, J.; Jiang, Q.; Dong, X.; Dong, K.; Jiang, H. How does industrial structure adjustment reduce $CO_2$ emissions? Spatial and mediation effects analysis for China. *Energy Econ.* **2022**, *105*, 105704. [CrossRef]
30. Wong, J.K.W.; Li, H.; Wang, H.; Huang, T.; Luo, E.; Li, V. Toward low-carbon construction processes: The visualisation of predicted emission via virtual prototyping technology. *Autom. Constr.* **2013**, *33*, 72–78. [CrossRef]
31. Chen, Y.S.; Lai, S.B.; Wen, C.T. The influence of green innovation performance on corporate advantage in Taiwan. *J. Bus. Ethics* **2006**, *67*, 331–339. [CrossRef]
32. Wang, Q.; Qu, J.; Wang, B.; Wang, P.; Yang, T. Green technology innovation development in China in 1990–2015. *Sci. Total Environ.* **2019**, *696*, 134008. [CrossRef] [PubMed]
33. Li, Y.; Muhammad, R.; Li, X.; Muntasir, M.; Abraham, A.A.; Sununu, I.B.; Tomiwa, S.A. Determinants of carbon emissions in Argentina: The roles of renewable energy consumption and globalization. *Energy Rep.* **2021**, *7*, 4747–4760.
34. Ehrlich, P.R.; Holdren, J.P. Impact of Population Growth: Complacency concerning this component of man's predicament is unjustified and counterproductive. *Science* **1971**, *171*, 1212–1217. [CrossRef]
35. Dietz, T.; Rosa, E.A. Effects of population and affluence on $CO_2$ emissions. *Proc. Natl. Acad. Sci. USA* **1997**, *94*, 175–179. [CrossRef] [PubMed]
36. Hansen, B.E. Threshold effects in non-dynamic panels: Estimation, testing, and inference. *J. Econ.* **1999**, *93*, 345–368. [CrossRef]
37. Shen, H.; Huang, N. Can carbon emission trading mechanism improve enterprise value. *Financ. Trade Econ.* **2019**, *40*, 144–161.
38. Hu, Y.; Guo, C. Impact of Digitalization on Carbon Emission Intensity of Manufacturing Enterprises: Theoretical Modeling and Mechanism Test. *J. Beijing Univ. Technol.* **2019**, *23*, 153–168.
39. Wu, F.; Hu, H.; Lin, H.; Ren, X. Enterprise Digital Transformation and Capital Market Performance: Empirical Evidence from Stock Liquidity. *Manag. World* **2021**, *37*, 130–144.
40. Qi, S.; Lin, S.; Cui, J. Can the environmental rights trading market induce green innovation?—Evidence based on green patent data of Chinese listed companies. *Econ. Res.* **2018**, *53*, 129–143.
41. Li, Q.; Xiao, Z. Heterogeneous environmental regulation tools and green innovation incentives: Evidence from green patents of listed companies. *Econ. Res. J.* **2020**, *55*, 192–208.
42. Li, X.; Liu, J.; Ni, P. The impact of the digital economy on $CO_2$ emissions: A theoretical and empirical analysis. *Sustainability* **2021**, *13*, 7267. [CrossRef]
43. Wang, L.; Chen, Y.; Ramsey, T.S.; Hewings, G.J. Will researching digital technology really empower green development? *Technol. Soc.* **2021**, *66*, 101638. [CrossRef]

44. Yuan, C.; Xiao, T.; Geng, C.; Sheng, Y. Digital Transformation and Division of Labor between Enterprises: Vertical Specialization or Vertical Integration. *China Ind. Econ.* **2021**, *9*, 137–155.
45. Xiao, H.; Yang, Z.; Liu, M. The Promotion Effect of Corporate Digitalization on Corporate Social Responsibility: A Test of Internal and External Dual Paths. *Bus. Manag. J.* **2021**, *43*, 52–69.
46. Si, H.; Tian, Z.; Guo, C.; Zhang, J. The driving effect of digital economy on green transformation of manufacturing. *Energy Environ.* **2023**. [CrossRef]
47. Xu, J.; Yu, Y.; Zhang, M.; Zhang, J.Z. Impacts of digital transformation on eco-innovation and sustainable performance: Evidence from Chinese manufacturing companies. *J. Clean. Prod.* **2023**, *393*, 136278. [CrossRef]
48. Xiang, X.; Yang, G.; Sun, H. The impact of the digital economy on low-carbon, inclusive growth: Promoting or restraining. *Sustainability* **2022**, *14*, 7187. [CrossRef]
49. Lin, X.; Zhu, X.; Han, Y.; Geng, Z.; Liu, L. Economy and carbon dioxide emissions effects of energy structures in the world: Evidence based on SBM-DEA model. *Sci. Total Environ.* **2020**, *729*, 138947. [CrossRef]
50. George, G.; Merrill, R.K.; Schillebeeckx, S.J.D. Digital sustainability and entrepreneurship: How digital innovations are helping tackle climate change and sustainable development. *Entrep. Theory Pract.* **2021**, *45*, 999–1027. [CrossRef]
51. Xue, L.; Zhang, Q.; Zhang, X.; Li, C. Can digital transformation promote green technology innovation? *Sustainability* **2022**, *14*, 7497. [CrossRef]