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Research on the impact of digital transformation on green development of manufacturing enterprises

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Digital development is changing with each passing day, and the traditional manufacturing industry is gradually shifting from extensive development to intensive development, the most prominent manifestation of which is the digital transformation and development of enterprises. This paper first discusses the internal mechanism of digital transformation promoting the green development of manufacturing enterprises from three aspects: product greening, technology greening and investment greening. Then, based on the panel data of China's listed manufacturing enterprises from 2011 to 2019, the fixed effect model, two-stage least squares method, mediating effect model and moderating effect model were used to test the relationship between them. The results show that digital transformation can promote the green development of manufacturing enterprises, and this conclusion still holds after a series of robustness tests. The empirical results of the mediating effect model show that digital transformation promotes the green development of manufacturing enterprises through three mediating paths: increasing green product output, technological innovation level and green investment level. Moreover, the promoting effect of digital transformation on the green development of enterprises will be moderated by the heterogeneous effect of environmental uncertainty. Therefore, accelerating the digital development of enterprises and promoting the construction of digital China is conducive to the green development of enterprises, and finally realizing the common development of digitalization and greening.

KEYWORDS

digital transformation, green development, green production, green technology, green investment, environmental uncertainty

1 Introduction

In recent years, although China's total economic volume has achieved breakthrough development, the quality of economic development is still at a relatively low stage, especially the development of the ecological environment. According to statistics, the ratio of the added value of China's manufacturing industry to GDP has dropped from 31.5% in 2010 to 26.2% in 2020 (CSY, 2021), but the carbon emissions of the manufacturing

industry have increased from 81.5503 million tons in 2010 to 10.251 billion tons in 2020(CESY, 2021), which indicates that manufacturing industry is the main battlefield for China to reduce carbon emissions, and it is also a key area for China to achieve the "dual carbon" goal. China's economic development has entered a new era, requiring the real economy to improve clean production capacity and reduce production pollutant emissions, especially in the manufacturing sector, to push the transformation of the real manufacturing economy from an extensive development model to an intensive development, and to further achieve green development.

In the context of increasingly fierce global economic competition, digitalization and green development have become two major trends of global economic and social transformation. The advantage of digitalization is to make full use of data from various fields, optimize the efficiency of machines and production processes through the comprehensive application of massive data, perfect energy efficiency and reduce emissions. Digitalization provides a full-chain support for improving equipment connectivity, production efficiency and policy precision for green development (Ministry of Commerce of the People's Republic of China, 2022). Thus, the study of digital transformation and enterprise green development has important practical and practical significance.

How to promote the green development of the manufacturing industry and ensure the smooth realization of the "double carbon" goal has become a huge challenge. To achieve green development, we must find a suitable development model. With the continuous expansion of the scale of digital infrastructure and the rise of digital technologies such as big data, the Internet of Things and artificial intelligence, these provide a practical path for the green development of the manufacturing industry. The digital transformation and development of traditional enterprises using digital infrastructure and emerging digital technologies is the kernel of China's digital economy development (Fan and Hongxia, 2019), and it is also the vital driving force for China's economic development. The report of the 19th National Congress of the Communist Party of China clearly stated that "to further the deep integration of the Internet, big data, artificial intelligence, etc. With the real economy"(Xi Jinping, 2017). The content of the report emphasizes that the production, operation and management of real enterprises should be actively incorporated into the application of digital technology, and highlights the important position of digital transformation of enterprises in the development of the national real economy (Kedi, 2020). Based on this, this paper will deeply explore whether digital transformation can promote the green development of enterprises, which has laid a theoretical foundation and reference experience for the green development of enterprises in China.

The green development of enterprises has the characteristics of periodicity and complexity (Kedi, 2020), which leads to the impact of the green development of enterprises in many aspects. In the era of vigorous development of the digital economy, the level of digital infrastructure construction and the application of digital technology are constantly improving, which has advanced the economic transformation and upgrading of real enterprises (Yong, 2020; Xiujuan and Rui, 2022). There are abundant research systems on how digital development enables green development of manufacturing enterprises, but the conclusions are quite different. Some scholars have found that external factors such as digital economy (Jing and Xi, 2022), artificial intelligence (Fei et al., 2022), internet development (Jinqiu and Xinfeng, 2021) and big data applications (Xianchun et al., 2019) have a linear positive relationship with the green development of enterprises. A few scholars believe that digital development has a certain degree of threshold effect on the green development of enterprises (Wenxian and Xuefeng, 2021). The literature on the impact of digitalization on the green development of enterprises mainly focuses on the relationship between digital transformation and enterprise green technology innovation (Deyong et al., 2022; Qiongwen and Siyu, 2022). Green technology innovation is the vital driving force for enterprises to achieve green development, and the driving effect of green technology innovation in enterprise digitalization can inject new impetus into the green development of enterprises.

The green development is the important basis for the high-quality economic development (Jing and Xi, 2022). In terms of ecological footprint, Can, M et al. (2022) thought that the green products in a country's trade basket can reduce that country's ecological footprint. Hongli et al. (2020) empirically tested the provincial panel data and showed that the development of green finance could significantly inhibit carbon emissions and further green economic development. Zengfu et al. (2022) found that the green credit can inhibit carbon dioxide emissions by promoting green technology innovation and optimizing industrial structure, and its inhibitory effect becomes more significant with the expansion of the scale of green credit. At the same time, Lijun (2021) believes that the implementation of carbon neutral green transformation to achieve green development is conducive to the improvement of ecological and environmental quality, and there is a U-shaped change between the two. In terms of residents' health, residents' health is not only related to individual characteristics, but also closely related to external factors that affect quality of life (Ojala A et al., 2019, Dzhambov A M et al., 2019). Among them, the ecological environment is an important external factor affecting the health of residents. Actively promoting green development can realize the organic unity of ecological environment improvement and social and economic development, thus improving residents' happiness and the overall health level (Shunyi, 2017).

From the above analysis, this paper summarizes the existing literatures as follows: Firstly, most of the previous studies have studied the green driving effect of macroscopic external factors on enterprises. Few studies have examined the relationship between the digital development of enterprises themselves and the green

development of enterprises from a micro perspective. Secondly, most of the literature on the impact mechanism of digital development on green development focuses on the research object, while the green development of enterprises is the result of the joint creation of the government, enterprises and citizens. Thirdly, most of the previous studies used the data of regional internet development, artificial intelligence development, robotics and other levels to represent the level of digital development, ignoring the heterogeneity of micro-individual development, resulting in the inability to accurately measure the digital development level of micro-individuals. Finally, the green development has the positive effect on the ecological footprint, carbon emission, environmental quality and residents' health.

Aim at the shortcomings of the existing literature, this paper will fill these gaps and the possible marginal contributions of this paper are as follows. The literature on the impact of digital transformation on the green development of manufacturing enterprises and its existing impact mechanism enrich the existing theoretical study on digital development and green development. This paper uses Python to analyze the annual reports of listed manufacturing companies, and constructs a measure of the digital development level of enterprises. Incorporate environmental uncertainty into the investigation framework of the impact of digital transformation on the green development of enterprises, and integrate the level of individual digital development with changes in the internal environment. The mediation effect model is used to empirically test the internal mechanism of digital transformation affecting the green development of enterprises, and further evaluate the economic benefits and market value caused by the green driving effect of digital transformation.

The remaining of the study is constructed as follows. Section 2 presents theoretical analysis and research hypotheses. Section 3 presents research design about models, data sources and some explanation. Section 4 presents empirical results and analysis from different regressions. Section 5 provides conclusions and policy implications.

2 Theoretical analysis and research hypotheses

2.1 Digital transformation and green development of enterprises

Enterprise green development is inseparable from product greening, technology greening and investment greening (Joint Research Group of the World Bank and the Development Research Center of the State Council, 2012). This paper mainly analyzes the relationship between enterprise digital transformation and green development from the perspective of product effect, technology effect and investment effect of enterprise digital transformation.

First, the product level. Digital transformation can integrate the production and sales of enterprise products through a network platform. First of all, in the process of product production, enterprises take big data, artificial intelligence, *etc.* As the core technology of the enterprise to create intelligent manufacturing, optimize the production process, and perfect the production efficiency of the enterprise. The application of digital technology by enterprises can obtain relevant resource information and financing information that are beneficial to production input from the outside, break the situation of blocked enterprise information, form an accurate match between domestic demand and external supply, and reduce enterprise information costs. Secondly, in the process of product management, digital transformation can effectively solve business problems such as product inventory, product marketing, and product promotion by virtue of digital advantages, and achieve the goal of high efficiency and high quality in the whole process of product management. Finally, in the process of product sales, the key content of the digital transformation of enterprises—big data. By collecting massive market information, simulating customer needs, *etc.*, using big data processing analysis, risk assessment and other means, it can connect consumer preferences with enterprises. The combination of product features controls the cost of sales of the enterprise and realizes the intelligent sales of products.

Second, the technical level. With the continuous integration of the digital economy and the real economy, the application scope of digital technology has expanded rapidly. The digital transformation of enterprises is an important micro-foundation for achieving high-quality economic development, and its effect on technological innovation of enterprises is becoming more and more obvious (Guosheng and Pengfei, 2022). Especially the green technology innovation of enterprises (Deyong et al., 2022). The green technology innovation effect of digital transformation is mainly reflected in the following points: Firstly, the application of digital technology can reduce resource misallocation (Bingzhan and Jiantong, 2020), effectively coordinate external resources, and better cross-enterprise cooperation, innovation and communication capabilities (Guosheng et al., 2021), which is conducive to promoting the exchange of knowledge and resources of heterogeneous enterprises and enriching the types of green technology innovation resources of enterprises. Second, Schumpeter's (1977) innovation theory proposes that the reorganization of production factors belongs to a type of industrial enterprise innovation. As the central production factor for the digital transformation and development of enterprises, the reorganization and integration of digital and traditional production factors and resources can contribute the efficiency of factor allocation in the process of production and operation and pollution treatment of enterprises, and push the "production-governance" to form a standardized and systematic model, so as to improve the green technology level of enterprises. Third, digital transformation can refine the employment level of

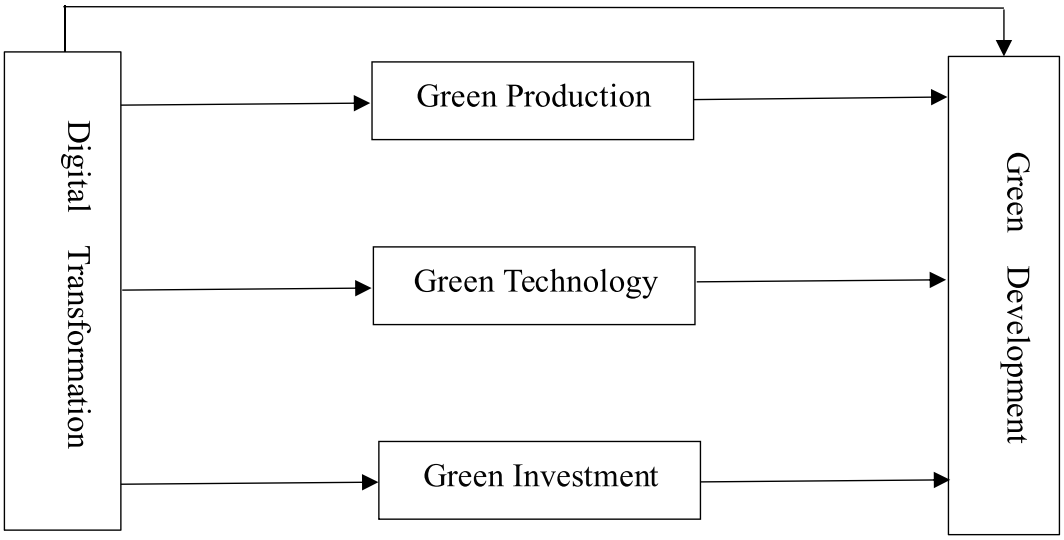

FIGURE 1
Digital transformation and green development.

high-skilled talents (Chenyu, 2022). At the same time, enterprise employees can use digital technology equipment to learn new knowledge and skills from the outside world, thereby improving the overall human capital level of the enterprise (Tong and Guowang, 2022). Digital development can stimulate the productive potential of labor, spread the scope of technology spillovers, and ultimately boost green technology innovation in enterprises.

Finally, the investment level. Green investment is the central part of economic sustainable development and will have a positive impact on the welfare of human beings (Lili and Yao, 2006). Among them, human well-being is one of the important indicators of human welfare, Can, B., et al. (2022) found that the renewable energy consumption and green trade openness have made a remarkable positive contribution to human well-being. At the same time, the regional green investment also can better the green welfare level of resident (Xianchun et al., 2020) and has the negative effect on the environmental pollution (Ren et al., 2022).

Digital transformation is the use of digital technology to carry out production and operation activities, and its development should have an impact on the green investment behavior of manufacturing enterprises. On the one hand, digital transformation can effectively alleviate the problem of information asymmetry. Through digital empowerment, enterprises can efficiently obtain investment and financing information, improve information acquisition capabilities, and perfect enterprise investment efficiency (Lei et al., 2022). The information advantage of corporate investment will help companies choose energy-saving, material-saving, waste-free or less-waste product projects, and carry out project investment activities within the environmental pollution standards of the government or relevant regulatory agencies to avoid sunk costs caused by environmental failure. On the other hand, digital transformation is conducive to the establishment of a digital investment decision-making system for enterprises, and contributes enterprises to realize self-interested behavior of investment (Can Z. et al., 2020). Under the background of the "two mountains" theory, green investment has played an important role in promoting environmental improvement (Yufeng and Yanbai, 2021). Manufacturing companies will actively seek to invest in green production processes by taking advantage of the low-cost advantage of digital technology. The main purpose is to protect the environment and enterprise production at the same time, ensure the sustainable development of pollution prevention and control actions, and finally achieve the goals of maximizing investment utility and capital profit.

Digitalization is a new driving force for enterprise development (Jia and Shilong, 2022), which can push the manufacturing industry to achieve refined control, refined operation and precise management of the entire enterprise process, and promote the green development of enterprise products. The application of digital technology can significantly exert the effect of green technology innovation. The higher the level of green technology innovation, the stronger its clean production capacity, which will significantly reduce the level of environmental pollution (Ruizhi et al., 2021). Digital transformation advances enterprises to invest in low-energy, low-pollution, and sustainable product production projects, actively respond to the call for pollution prevention and control, reduce production pollution, and help enterprises

achieve green investment. Based on the above analysis, in the boom of digital economy development, the digital transformation of enterprises can have a positive impact on the green development of enterprises. The influencing figure is shown below(see Figure 1) and the following assumptions are put forward.

H1a: *Digital transformation can promote the green development of manufacturing enterprises.*

H1b: *The impact of digital transformation on the green development of manufacturing enterprises is mainly achieved through three paths of product greening, technology greening and investment greening.*

2.2 The moderating effect of environmental uncertainty

The activities of enterprise digital transformation are carried out in the environment, but the environment is characterized by uncertainty. Environmental uncertainty is a kind of complex and multi-dimensional external factors. Ghosh and Olsen (2009)divide environmental uncertainty into moderate environment, random environment and exclusive environment according to the direction of influence. Under the new economic development situation, in order to adapt to changes in the external environment, enterprises need to take corresponding measures to carry out digital transformation and get rid of the disadvantages of traditional business models (Zhen, 2022). The digital transformation and green development of enterprises are carried out in the same environment, and there is a close relationship between the characteristics of environmental uncertainty and the two. The heterogeneous nature of environmental uncertainty has different effects, mainly for the following reasons. First, a moderate environment can create a suitable development environment for the digital transformation of enterprises, boost enterprises to accelerate their digital transformation, and ensure that enterprises can maintain a low-pollution production model while developing efficiently. At the same time, in a moderate environment, manufacturing enterprises will follow the vigorous development trend of the digital economy, obtain digital dividends, and push the high-quality development of enterprises (Tao et al., 2020). Second, the random environment will cause enterprises to fail to accurately identify the external environment and make accurate analysis and judgment. The unstable external environment is not conducive to enterprises' product marketing strategy formulation, project decision-making and investment activities, and the frequency of use of digital technology will decrease, which will slow down the release of "digital dividends". Third, an exclusionary environment reduces a company's digital development resources and potential development opportunities. Based on the possibility of risk, companies will consider reducing digital capital investment. At the same time, external investment institutions will also reduce the scale of investment in digital industries (Lei et al., 2022). This will hinder the production and operation of enterprises and the development of technological innovation, which is not conducive to the green effect of digital technology. Based on the above analysis, the heterogeneity of environmental uncertainty may play a different moderating effect in the process of digital transformation affecting the green development of enterprises. The moderating effect figure is shown below (see Figure 2) and the following hypothesis is proposed.

H2a: *The moderate environment positively regulates the impact of digital transformation on the green development of enterprises.*

H2b: *The random environment negatively regulates the impact of digital transformation on the green development of enterprises.*

H2c: *The exclusionary environment negatively regulates the impact of digital transformation on the green development of enterprises*.

3 Research design

3.1 Data sources

Since the nationwide broadband acceleration in 2011, the scale of China's digital development has continued to expand, and the number of digital transformation enterprises has also increased. Hence, this paper selects China's listed A-share manufacturing enterprises from 2011 to 2019 as the research sample, and processes the data as follows. A. Exclude ST, ST*, PT enterprise samples. B. Exclude financial, information technology and electronic equipment manufacturing enterprise samples. C. Exclude enterprise samples with missing data. D. Exclude enterprises in Tibet. E. In order to eliminate the influence of extreme values on the results, 1% tail reduction processing was performed on the sample data. After the above processing, the sample size of 16,482 manufacturing enterprises was finally obtained.

The data sources of this paper mainly come from: WIND database, CASMAR database, statistical yearbooks of provinces and prefecture-level cities, and environmental statistical yearbooks of provinces and prefecture-level cities.

3.2 Model

In order to verify the impact of digitalization on the green development of enterprises, this paper refers to the research model of Pang Ruizhi et al.(2021)and Li Ying and Xu

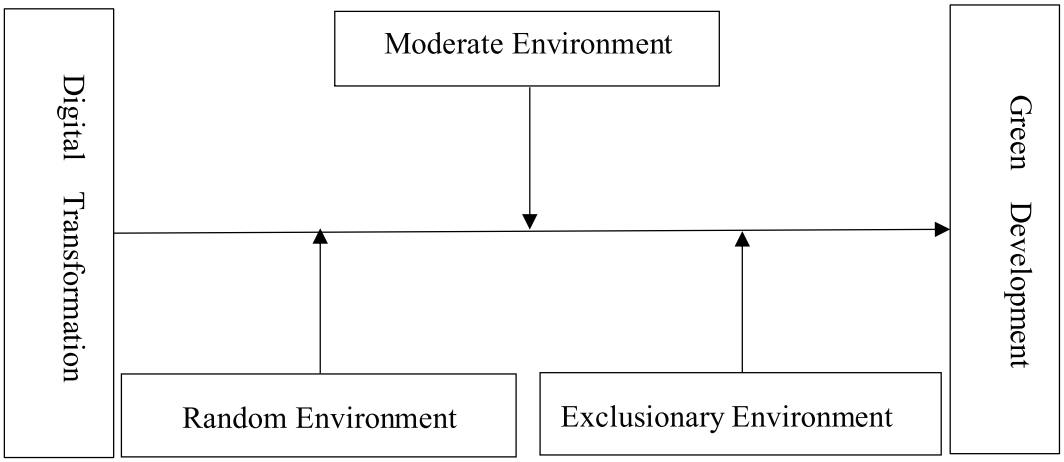

FIGURE 2
The moderating effect of environmental uncertainty.

Yuemeng(2021)and then constructs the following empirical model.

$$gdi,t = \alpha 0 + \alpha 1 digi,t + \sum \alpha Xcontrols + \varepsilon it \quad (1)$$

In Equation, $\boldsymbol{gd_{i,t}}$ is the green development level of company $\boldsymbol{i}$ at time $\boldsymbol{t}$, $\boldsymbol{dig_{i,t}}$ is the digitalization level of company $\boldsymbol{i}$ at time $\boldsymbol{t}$, $\boldsymbol{X_{controls}}$ is the control variable at the company, industry and regional levels, and $\boldsymbol{\varepsilon}$ is the random disturbance item.

Compared with the empirical model used by Jinqiu and Xinfeng (2021), the DID model was mainly used to examine the impact of related digitalization policies. However, this paper mainly studies whether the digital transformation of manufacturing enterprises would affect the green development of manufacturing enterprises, and focuses on the consequences of the digital transformation behavior of manufacturing enterprises from a micro perspective. So, the adoption of the above model is more consistent with the investigation content of this paper.

In order to further test the impact mechanism of digital transformation on the green development of enterprises, this paper constructs the following mediation effect model.

$$Medi,t = \beta 0 + \beta 1 digi,t + \sum \beta Xcontrols + \varepsilon it \quad (2)$$

$$gdi,t = \delta 0 + \delta 1 digi,t + \delta 2 Medi,t + \sum \delta Xcontrols + \varepsilon it \quad (3)$$

In equations, $\boldsymbol{Med_{i,t}}$ is the mediating variable of company $\boldsymbol{i}$ at time $\boldsymbol{t}$, where $\boldsymbol{\alpha_1}$ is the total effect of digital transformation on the green development of enterprises, $\boldsymbol{\delta_1}$ is the direct effect, and $\boldsymbol{\beta_1{*}\delta_1}$ is the degree of the mediating effect of ***Med***. Among them, ***Med*** mediating variables mainly include the scale of green products (*gp*), the level of green technology innovation (*gt*)and the level of green investment(*gi*).

On the basis of formula, we add environmental uncertainty and external factors as moderators. The moderating effect of environmental uncertainty in the process of digital transformation affecting the green development of enterprises is tested, and the following moderating effect model is constructed.

$$gdi,t = \gamma 0 + \gamma 1 digi,t + \gamma 2 Mediai,t + \gamma 3 digi,t{*}Mediai,t + \sum \gamma Xcontrols + \varepsilon it \quad (4)$$

In formula, $\boldsymbol{Media_{i,t}}$ is the adjustment variable of $\boldsymbol{i}$ company at time $\boldsymbol{t}$, where $\boldsymbol{\gamma_3}$ is the adjustment variable coefficient, if $\boldsymbol{\gamma_3}$ is positive, it means that the adjustment variable positively boosts the digital transformation and exerts the green effect, otherwise, then Indicates that the negative side inhibits digital transformation from exerting a green effect.

3.3 Variable description

3.3.1 Explained variable

Green Development (gd). Referring to Li Ying and Xu Yuemeng (2021), the green total factor productivity of enterprises is taken as a proxy variable for the green development of enterprises. This paper uses the SBM model and the GML index to measure the green total factor productivity (GTFP)that includes undesired outputs. GTFP includes capital input, labor input, desired output and undesired output. The calculation methods of these four indicators are as follows. Capital investment, $Kt = Kt - 1\,(1 - \lambda 1) + It/Pt$. Where K_t is the capital stock of the enterprise in period t, λ_1 is 5%, I_t is the investment in fixed assets of the enterprise in period t, and P_t is the investment price index of the province where the enterprise is located in period t. Labor input, select the total number of employees in the current year as a substitute variable. Expected output, select the total revenue of the company's main business in

TABLE 1 Descriptive statistics of variables.

Variable name	Variable symbol	Sample numbers	Average value	Standard deviation	Minimum Value	Maximum value
green development	gd	16,482	7.024	2.203	2.795	10.471
digital level	dig	16,482	0.110	0.188	0.0001	1
green product	gp	16,482	21.195	3.177	0	28.036
green technology	gt	16,482	0.753	0.071	0	1
green investment	gi	16,482	0.400	0.123	−5.229	1
moderate environment	me	16,482	4.834	7.809	−7.640	56.109
random environment	re	16,482	3.449	4.195	0.095	132.884
repulsive environment	ee	16,482	0.027	0.148	−7.700	4.707
enterprise scale	scale	16,482	0.032	2.243	0.255	56.963
enterprise performance	roa	16,482	0.582	0.155	0.013	1.012
shareholding ratio of the first shareholder	h1	16,482	0.345	0.150	0.003	0.990
nature of equity	kind	16,482	1.665	0.599	1	4
economic development level	edl	16,482	0.452	0.269	0.006	10.482

the current year as a substitute variable. Unexpected output, which mainly includes the CO2, SO2 and other pollutant emissions of the enterprise in the current year, $Eij = [(Pkj/\sum Pkj)/(Ok/\sum Ok)]^{*}Ykj^{*}(Oi/\sum Oi)$ E_{ij} is the emission of pollutants of type j of enterprise i, P_{kj} is the emission of pollutants of type j of prefecture-level city k, O_k is the total output value of prefecture-level city k, and O_i is the total industrial output of enterprise i. Finally we get: $Ei = \sum Eij$ Among them, E_i is the undesired total output of enterprise i, which represents the total emission of all pollutants of type j.

3.3.2 Core explanatory variables

Level of digital transformation (dig). Drawing on the method of Chenyu (2022), this paper uses Python to perform text analysis and information crawling on the annual reports of listed companies, build a quantifier table, and use the proportion of the number of words in the annual report of the company as the digital transformation level of the company. At the same time, the ratio of the number of some intangible assets related to digital transformation in the intangible assets at the end of the year to the total number of intangible assets in the financial reports of listed companies is adopted. Take it as a replacement variable for robustness testing (Huaijin et al., 2020), and denote it as *iadig*.

3.3.3 Mediating variables

Green Product Scale (*gp*). Drawing on the investigation of Xuan and Jun (2022), the total output value of the clean energy, environment-friendly, renewable energy and other products of the enterprise is selected as the green product scale (*gp*) according to the type and production scope of the production and operation license of the enterprise. Proxy variable.

Green technology innovation level(*gt*). Drawing on the investigation of Deyong et al. (2022), the innovation is classified according to the IPC code published by the World Intellectual Property Organization, and the ratio of the number of enterprise green patent applications to the total number of patent applications is selected as the proxy variable of green technology innovation(*gt*).

Green investment level(*gi*). Drawing on the investigation of Dongming (2020), using Python crawler technology to collect data on a series of expenses related to environmental construction and pollution control in the annual report of the construction project in progress, and select the total amount of the above projects as the green investment level of the enterprise(*gi*) proxy variable.

3.3.4 Adjustment variables

Based on the heterogeneity of environmental uncertainty, this paper refers to the practice of Qiongwen and Siyu (2022), and selects the average sales growth rate of listed manufacturing companies in the past 5 years as a proxy variable for the moderate environment (me). The unstable part of the operating income of listed manufacturing enterprises in the current year is selected as the proxy variable of the random environment (re). Select the ratio of accounts receivable to total sales revenue of listed manufacturing enterprises in the current year as a proxy variable of the exclusionary environment (ee). At the same time, according to the practice of Shen Huihui et al. (2012), the above proxy variable data are all adjusted by industry, and the external influence of the industry is excluded. In addition, to avoid possible multicollinearity issues between the moderator variables and the core explanatory variables, the three moderator variables were decentralized.

TABLE 2 Benchmark regression results.

	(1) gd	(2) gd	(3) gd
dig	0.899*** (7.40)	0.832*** (7.76)	0.865*** (7.04)
scale		0.051*** (10.02)	0.045*** (8.93)
roa		0.2354*** (15.24)	2.168*** (12.70)
kind		−0.391*** (−8.93)	−0.170*** (−2.83)
h1		−0.450*** (−2.59)	−1.659*** (−7.70)
edl		−0.214*** (−3.14)	−0.521*** (−7.12)
_cons	6.925*** (406.99)	6.409*** (52.89)	6.757*** (47.83)
R^2	0.004	0.025	0.029
N	16,482	16,482	16,482
chi (CESY, 2021)			187.200
p-value			0.000
TFE	YES	NO	YES
IFE	YES	NO	YES

Note: ***, ** and * indicate significance at the 1%, 5% and 10% significance levels, respectively; ( ) is the t/z statistic for parameter estimation.

3.3.5 Control variables

On the basis of referring to relevant literature, this paper selects the following control variables. Enterprise scale (scale), expressed as the natural logarithm of the total assets of the enterprise. The operating performance of the enterprise (roa), which is expressed by the profit rate of the total assets of the enterprise. The shareholding ratio of the largest shareholder of the enterprise (h1). The nature of the enterprise's equity (kind), which is expressed by a dummy variable. If the enterprise is a state-owned enterprise, it is 1; otherwise, it is 0. Regional economic development level (edl), which is represented by a dummy variable. If the enterprise is in the eastern region, it is 1; otherwise, it is 0. The descriptive statistics of the variables in this paper are shown in Table 1.

4 Empirical results and analysis

4.1 Benchmark regression

Table 2 reports the overall test results of the impact of digital transformation on the green development of manufacturing enterprises. In this paper, it is found by Hausman test that the chi value is 187.200 and the *p*-value value is 0.000, so the regression model in this paper is selected as a fixed effect model for empirical analysis. Column in Table 2 is the regression result with only core explanatory variables added. It can be seen that digital transformation has significantly improved the green development level of manufacturing enterprises. Column (2) and (3) of Table 2 are the regression results after adding control variables, column (2) is the result of random effect regression, and column (3) is the result of "time-individual" fixed effect regression. From the results in columns (1) and (2) of Table 2, it can be found that digital transformation can promote the green development of manufacturing enterprises at the 1% significance level, assuming that H1a is established. The results of the benchmark regression in this paper are consistent with the conclusions of Han Jing and Chen Xi (2022) on the impact of digital economy at the macro level on green development. This paper shows that digitization at the micro level can promote the green development of manufacturing enterprises.

From the results of the control variables, large-scale enterprises with excellent business performance have high development level and strong capital liquidity, and the green development performance of enterprises is better. Non-state-owned enterprises and enterprises with a high proportion of the first shareholder, the green development of enterprises is relatively slow. For manufacturing enterprises in areas with a high level of economic development, they may be too eager to expand the scale of output, ignoring environmental protection and environmental governance.

4.2 Robustness test

In order to ensure the reliability of the study conclusions, this paper carried out a series of robustness tests as follows. Mainly include Replace the core explanatory variables. Drawing on the practice of Huaijin et al. (2020), the ratio of intangible assets related to digital transformation to total intangible assets is used as the substitute variable for digital transformation. The results in column (1) of Table 3 show that digital transformation measured

TABLE 3 Robustness test results.

	(1) gd	(2) op-gd	(3) o-gd	(4) gd	(5) gd
iadig	1.239*** (11.14)				
dig		0.871*** (6.98)	0.866*** (6.96)		
L.dig				0.896*** (6.10)	
L2.dig					0.633*** (3.67)
CV	YES	YES	YES	YES	YES
_cons	1.020*** (6.87)	7.325*** (74.71)	7.336*** (74.94)	7.792*** (52.87)	7.811*** (47.26)
R^2	0.186	0.017	0.017	0.024	0.024
N	16,482	16,482	16,482	12,780	10,559
TFE	YES	YES	YES	YES	YES
IFE	YES	YES	YES	YES	YES

Note: ***, ** and * indicate significance at the 1%, 5% and 10% significance levels, respectively; ( ) is the t/z statistic for parameter estimation.

by intangible assets still promotes the green development of manufacturing enterprises at the 1% significance level. Replace the explained variable. The green development level of enterprises is measured by the OP method and the conventional method, and the results in the columns (3) of Table are still significantly positive. Lagged regression analysis of core explanatory variables. Using lag-period regression to eliminate the problem of result bias caused by endogeneity, this paper re-introduces all the core explanatory variables into one lag period and two lag periods for empirical regression. The results are shown in columns (4) and (5) of Table 3. The regression coefficient of the lag period of digital transformation is still significantly positive, which is consistent with the benchmark regression results. After considering the measurement of the core explanatory variables, the measurement of the explained variables, and the endogeneity problem, the empirical results are still consistent with the benchmark regression results, that is, the conclusions of this paper are robust.

4.3 Test of mediation effect

On the basis of the benchmark model, a mediating effect model is constructed to verify that digital transformation affects the green development of manufacturing enterprises. The first step is to regress the core explanatory variables and mediating variables. In the second step, the mediator variable is included between the explained variable and the core explanatory variable, and the three are put together for regression. The third step is to calculate the influence degree of the mediation effect according to the regression coefficient. For the mechanism test of green products, the total output value of enterprise green products is selected as a substitute variable, and the regression results are shown in the columns (2) of Table 4. Digital transformation can further the scale of green products of manufacturing enterprises at a significant level of 1%, thereby improving the green development of enterprises. For the mechanism test of green technology, the ratio of the number of enterprise green patent applications to the total number of patent applications is selected as a substitute variable, and the regression results are shown in the columns (4) of Table 4. Digital transformation can further the improvement of the green technology innovation level of manufacturing enterprises at a significant level of 1%, thereby improving the green development of enterprises. For the mechanism test of green investment, a series of costs related to environmental construction and pollution control in the construction project of the enterprise are selected, and the natural logarithm of the total cost is taken as the green investment substitute variable. The regression results are shown in the columns (6) of Table 4. Digital transformation can advance the level of green investment in manufacturing enterprises at the significant level of 1%, thereby improving the green development of enterprises. It is assumed that H1a holds.

In summary, the conclusions of the mediating effect model in this paper show that digital transformation can promote green development by improving the output of green products, green technology level and green investment level of manufacturing enterprises. However, few previous studies have studied the impact mechanism between digitalization and enterprise green development from the perspective of micro mechanism. The mechanism study in this paper provides a new perspective for future related investigation.

4.4 Moderating effect test

In order to verify the impact of the interaction between digital transformation and environmental uncertainty proposed in Hypothesis 2 on the green development of manufacturing enterprises, this paper constructs a

TABLE 4 Results of the mediation effect test.

	(1) gp	(2) gd	(3) gt	(4) gd	(5) gi	(6) gd
dig	0.998*** (15.73)	0.296*** (2.54)	0.042*** (8.78)	0.649*** (5.48)	0.086*** (15.51)	0.102 (0.90)
gp		0.6049*** (38.54)				
gt				5.9579*** (28.72)		
gi						1.658*** (9.70)
CV	YES	YES	YES	YES	YES	YES
_cons	21.085*** (2,374.21)	−5.830*** (−17.59)	0.748*** (54.53)	2.469*** (15.82)	0.391*** (53.03)	2.366*** (25.42)
R^2	0.017	0.098	0.005	0.058	0.017	0.151
N	16,482	16,482	16,482	16,482	16,482	16,482
TFE	YES	YES	YES	YES	YES	YES
IFE	YES	YES	YES	YES	YES	YES

Note: ***, ** and * indicate significance at the 1%, 5% and 10% significance levels, respectively; ( ) is the t/z statistic for parameter estimation.

moderating effect model, and selects the corresponding substitute variables for the moderating variables to carry out empirical regression analysis. This paper mainly analyzes the environmental uncertainty within the enterprise. The results in column (1) of Table 5 show that the regression coefficient of the digital transformation and the moderate environmental interaction term is positive, but the significance level is not high. It shows that the moderate environment can positively regulate the impact of digital transformation on the green development of manufacturing enterprises. This shows that the more stable internal factors such as strong capital liquidity and output stability of enterprises, the more obvious the promotion effect of digital transformation on the green development of manufacturing enterprises. The results in Table 5 (2) show that the regression coefficient of the interaction term between digital transformation and random environment is negative, and the coefficient of random environment is significantly negative, indicating that the random environment can play a significant negative role in the impact of digital transformation on the green development of manufacturing enterprises. Towards regulation. This shows that the uncertainty and randomness of the industrial environment and development environment faced by enterprises. The stronger the randomness of the output and the uncertainty of funds, the stronger the impact of digital transformation on the green development of manufacturing enterprises will be significantly weakened. The results in Table 5 (3) show that the regression coefficient of the interaction term between digital transformation and the exclusionary environment is significantly negative, indicating that the exclusionary environment has a significant negative adjustment effect on the impact of digital transformation on the green development of manufacturing enterprises. This shows that the stronger the degree of exclusion that enterprises face from the market industry environment, resource environment, and operational investment, *etc.*, the more obvious the weakening degree of the promotion effect of digital transformation on the green development of manufacturing enterprises.

Through the above analysis, we can conclude that the moderate environment can enhance the green promoting effect of digital transformation. Random environment and exclusionary environment will inhibit digital transformation and promote green development of manufacturing enterprises. This conclusion is consistent with the conclusions of Cheng Qiongwen and Lu Siyu (2022), who also believe that the promotion effect of digital technology application on enterprise green innovation will be differentially affected by environmental heterogeneity.

4.5 Heterogeneity test

Based on the theoretical analysis and the above analysis of the results, we believe that there may be heterogeneity in the promotion effect of digital transformation on the green development of the manufacturing industry. Accordingly, this paper refers to the study of Jiang Hongli and Jiang Pengcheng (2021), and conducts a subregional regression of the research sample from the differences in the external economic development level. There is a large gap in the level of economic development among various regions in my country. In order to avoid biased results caused by too many samples in the same region within the research sample. The regression results are shown in columns (2) of Table 6 in order. The results show that digital transformation has the most obvious promotion effect on the green development of manufacturing enterprises in the western region, followed by the promotion effect in the eastern region, and the promotion

TABLE 5 Moderating effect test results.

	(1) gd	(2) gd	(3) gd
dig	0.791*** (5.67)	0.945*** (6.68)	0.089 (0.80)
me	0.0641 (0.19)		
re		−0.013*** (−3.23)	
ee			2.785*** (25.86)
dig*me	1.219 (0.78)		
dig*re		−0.017 (−0.95)	
dig*ee			−1.344*** (−3.40)
CV	YES	YES	YES
_cons	6.919*** (280.22)	6.971*** (308.46)	−15.318*** (−33.85)
R^2	0.177	0.005	0.226
N	16,482	16,482	16,482
TFE	YES	YES	YES
IFE	YES	YES	YES

Note: ***, ** and * indicate significance at the 1%, 5% and 10% significance levels, respectively; ( ) is the t/z statistic for parameter estimation.

effect in the central region is weaker. This conclusion is consistent with the results of the benchmark regression. The economic development level of the region where manufacturing enterprises are located is relatively low, and the promotion effect of their digital transformation on the green development of enterprises is more obvious. This is mainly because the western region has disadvantages such as backward development of science and technology, poor resource endowment, and low degree of industry marketization. However, the technical effect and resource allocation effect of digital transformation can provide a strong impetus for the sustainable development of enterprises in the western region, and promote the green development of western enterprises. This is of great practical significance for promoting the western development to build a new economic development pattern and improving the efficiency of resource allocation in the western region.

At the same time, referring to the investigation of Zhao Chenyu (2022), according to the different element density within the enterprise, the human capital input elements of the enterprise are selected as the reference for the heterogeneity analysis. This paper selects the natural logarithm of the number of R&D personnel in the enterprise as the level of the human capital level of the enterprise, and calculates the median human capital level of the enterprise sample. The enterprise sample above the median of the human capital level of the sample is divided into high human capital enterprises (hhc), and the enterprise sample lower than the median human capital level of the sample is divided into low human capital enterprises (lhc), and empirical regression is carried out, the regression results are shown in the columns (5) of Table 6. From the regression results, it can be seen that the promotion effect of digital transformation on the current green development of enterprises with low human capital level is more obvious. This shows that under the condition of low resource endowment and R&D investment in low human capital enterprises, the advantages of efficient resource allocation and technological innovation spillover effect of digital transformation can significantly reduce the labor cost of enterprises, refine the level of enterprise innovation, and then contribute enterprises to achieve green development.

According to the above analysis, the promotion effect of digital transformation on green development of enterprises also has heterogeneous influence depend on where enterprises are located. It is consistent with the conclusion of most studies that enterprises in western China benefit more from digital transformation. Besides, the green promotion effect of digital transformation on manufacturing enterprises with lower human capital level is more obvious. This is mainly related to the resource endowment of enterprises. Digital transformation not only provides digital resources, but also perfects the efficiency of resource use of enterprises. Digital transformation will play a more obvious role in promoting green for enterprises with low initial resource endowment.

5 Policy recommendation

With the rapid development of digitalization in China, we need to know more about the real benefits of digital transformation. This paper finds that digital transformation can advance manufacturing enterprises green development by analyzing the relationship between digital transformation and enterprise green development. Based on the realistic background of digital development and its green effect,

TABLE 6 Heterogeneity test results.

	(1) east-gd	(2) central-gd	(3) west-gd	(4) hhc-gd	(5) lhc-gd
dig	0.774*** (5.68	0.678*** (1.65	1.362*** (3.65	0.791*** (4.54	0.853*** (4.21
CV	YES	YES	YES	YES	YES
_cons	7.902*** (51.51	8.607*** (27.46	6.664*** (20.61	8.750*** (43.07	6.771*** (37.51
R^2	0.020	0.039	0.057	0.029	0.024
N	11,156	3,201	2,125	8,060	8,422
TFE	YES	YES	YES	YES	YES
IFE	YES	YES	YES	YES	YES

Note: ***, ** and * indicate significance at the 1%, 5% and 10% significance levels, respectively; ( ) is the t/z statistic for parameter estimation.

this paper puts forward the following relevant policy implications.

5.1 Government level

We have found that digital transformation can promote the green development of manufacturing enterprises. Therefore, the local government should advocate suitable manufacturing enterprises for digital transformation. Firstly, governments can speed up the construction of digital infrastructure and expand the application scope of digital technology. This can make it easier for manufacturing enterprises to access digital-related information, better digital service level and service efficiency. Secondly, governments can encourage all industries to actively integrate digital technology applications in the process of enterprise production, operation, management and marketing, make full use of digital advantages, and absorb "digital dividends". Finally, government should be conscious of the importance of the green economy with digital. Governments accelerate economic development while realizing energy conservation, emission reduction and environmental governance by the expansion use of digitalization. Digital technology plays the vital role to boost the green and high-quality development of China's economy.

5.2 Industry level

Now that we've learned the benefits of digital transformation, digital is embedded in every industry. Accordingly, all industries should follow the trend and actively cooperate with scientific research institutions, universities and other institutions to create the green innovation and development platform and form a scientific and efficient digital industrial chain. This is especially true of the manufacturing sector, which accounts for a large proportion of national economic output. Consequently, the manufacturing industry should accelerate the pace of digital transformation. Digital transformation is an important development method for various industries to achieve high output while keeping environment sustainable and green. Every industry should increase digital investment and rationally deploy digital strategies and resource allocation.

5.3 Enterprise level

Enterprises are the central object of digital transformation. For enterprises to realize digital transformation, the following relevant measures should be provided: Firstly, The government should make relevant policies to further the digital transformation of enterprises. Secondly, The government can take some measures such as financial subsidies or tax incentives to guarantee that manufacturing enterprises have invest capital to accelerate the realization of digital transformation. Only when the vast majority of manufacturing enterprises have achieved digital transformation can the development of China's digital economy continue to move towards a stage of high-quality development. Finally, Enterprises should make full use of the advantages of industrial clusters, as soon as possible into the local digital industrial agglomeration. The formation of industrial clusters of Chinese digitalization and the rapid and efficient digital transformation of Chinese enterprises. It is the important guarantee for China to build key competitiveness with the digital economy in the future.

6 Conclusion

Based on the sample of China's listed A-share manufacturing enterprises from 2011 to 2019, we use the SBM model and GML index to disassemble and measure the green total factor productivity of enterprises. Then the OLS model, the mediation effect model and the adjustment model are constructed to empirically verify the impact of digital transformation on the green development of enterprises and

its existing impact mechanism. The paper found that Digital transformation can significantly promote the green development of enterprises, and this conclusion still holds after a series of robustness tests. It consists with the conclusions of Han Jing and Chen Xi (2022)on the impact of digital economy at the macro level on green development. We find that digital transformation can contribute the green development of manufacturing enterprises from the micro point of view. Digital transformation pushes the green development of enterprises by increasing the output of green products, improving the level of green technology innovation and expanding the scale of green investment. This conclusion is different from previous literature, there are few previous studies that have studied the impact mechanism between digitalization and enterprise green development from the perspective of micro mechanism. Obviously, the mechanism study in this paper provides a new perspective for future related investigation. Environmental uncertainty has played a moderating effect in the process of digital transformation promoting the green development of manufacturing enterprises, among which the moderate environment positively regulates the impact of digital transformation on the green development of enterprises. The random environment negatively adjusts the impact of digital transformation on the green development of enterprises; the exclusionary environment negatively adjusts the impact of digital transformation on the green development of enterprises. This conclusion is consistent with the conclusions of Qiongwen and Siyu (2022), who also believe that the promotion effect of digital technology application on enterprise green innovation will be differentially affected by environmental heterogeneity. The results of the heterogeneity test found that digital transformation can significantly promote the green development of western regions and enterprises with low human capital. This is mainly related to the resource endowment of enterprises. Enterprises with lower resource endowment would benefit more from the digital transformation process. Digital transformation not only provides digital resources, but also perfects the efficiency of resource use of enterprises. Digital transformation will play a more obvious role in promoting green for enterprises with low initial resource endowment. Last but not least, we also find that digital transformation is closely related to the level of green technology of enterprises by mediating test and green technology is the basis of green development. Manufacturing enterprises should attach importance to the development of green technology, increase the level of R&D investment in the field of green technology, cooperate with green investment, and further realize the ecological, green and high-quality development of enterprises.

Although we have verified the hypothesis of this paper through theoretical and empirical analysis, there are still some limitations in this paper. List the following: First, Limited by research methods, the research hypothesis of this paper is mainly based on theoretical analysis and related literature content and then use the empirical method to verify. We suggest that future investigation on this issue can build mathematical models and conduct qualitative analysis from the perspective of mathematics, and then select relevant data to verify qualitative conclusions. Secondly, due to the limited data, the time span of the sample in this paper is slightly shorter. In the future investigations, the time span can be extended to 2022 or choose the time span appropriate to the study related issues in your country. Finally, it is limited by the measure method of index, the GTFP measurement of micro-enterprises in this paper mainly refers to the measurement method of industry GTFP, and the results of measurement indicators may increase. Hence, in order to study the green development of enterprises more scientifically and rationally, the measurement methods on the GTFP level of enterprises still need to be further improved in future investigations. We suggest to build a set of comprehensive economic mathematical model to measure the GTFP level of enterprises, which will make the subsequent related issues more reasonable and accurate.

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

Conceptualization, methodology, formal analysis writing and data curation, SC, rewriting and review, TW, review and analysis, YY. All authors have read and agreed to the published version of the manuscript.

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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.

Publisher's note

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