Journal of Infrastructure, Policy and Development 2024, 8(15), 10348.
https://doi.org/10.24294/jipd10348

Article

The impact of digital green technology innovation in manufacturing on firm sustainability in China

Ziyi Jiao, Sutana Boonlua*, Jindarat Peemanee

Mahasarakham Business School, Mahasarakham University, Maha Sarakham 44150, Thailand
*** Corresponding author:** Sutana Boonlua, sutana.t@acc.msu.ac.th

CITATION

Jiao Z, Boonlua S, Peemanee J. (2024). The impact of digital green technology innovation in manufacturing on firm sustainability in China. Journal of Infrastructure, Policy and Development. 8(15): 10348. https://doi.org/10.24294/jipd10348

ARTICLE INFO

Received: 15 November 2024
Accepted: 2 December 2024
Available online: 10 December 2024

Abstract: More and more scholars are paying attention to the economic and environmental responsibilities undertaken by firms. Firm sustainability has become a hot topic in current research. This article aims to analyze the impact of various dimensions of digital green technology innovation on firm sustainability. The "digital green technology innovation" in this research is a new variable explored based on previous research, and the five dimensions of the variable are created based on the POLE theory. This research uses authoritative Chinese databases to collect data on various dimensions of digital green technology innovation and sustainable development of companies, and uses a fixed effects model for regression analysis. The results indicate that the implementation of various dimensions of digital green technology innovation will promote the firm sustainability. Moreover, in firms with strong profitability, this performance is significantly better than in those with weak profitability.

Keywords: digitalization; green technology; manufacturing; pole theory; environmental protection

1. Introduction

In the past decades, the development of industrialization has promoted social progress, but it has also caused some environmental consequences, such as global warming, resource shortage and environmental pollution (Gao et al., 2021). The emission of greenhouse gases (mainly carbon dioxide), air pollution caused by manufacturing industry and the burning of fossil fuels are considered as important factors causing global warming (Lee and Lee, 2022).

The concept of environment, society, and governance (ESG) has arisen, and sustainable development has taken center stage in all nations as a result of society's growing attention to environmental and social issues that could have an impact on future generations (Gao et al., 2021; Silva, 2023). People's awareness of environmental protection is constantly improving, and all countries are trying their best to achieve lasting sustainable development. Over 130 countries and regions have proposed "Zero Carbon" or "Carbon Neutral" climate goals (Zhao et al., 2022).

The World Commission on Environment and Development (WCED) advocates the harmonious development between man and nature, and describes sustainable development as the development that could meet the needs of contemporary people without damaging the ability of future generations to meet their own needs (Alsayegh et al., 2020). In recent years, green innovation and digital technology have become the keyways for the harmonious coexistence between man and nature (Zheng, 2023).

The WCED has put forward the macro concept of sustainable development for firm development, and more and more scholars apply the concept of "Sustainable

Development" to the firm level, that is, firms make rational use of resources and reduce the negative impact of production activities on the environment while meeting the continuous growth of their own profitability, so as to gain long-term support from internal and external stakeholders (Ali and Anwar, 2021). Digital technology and green innovation are crucial tools for achieving long-term objectives and strategic practices to address environmental challenges. These could support firms to achieve "Win-Win" between economic benefits and environmental benefits, and are crucial means of achieving for firms to sustainable development goals, all of which are guided by the dual-carbon goal (Xie and Zhu, 2021).

Manufacturing is an important pillar of the global economy because it greatly promotes economic development, creates employment opportunities and increases people's income (Abubakr et al., 2020). However, manufacturing also consumes a lot of energy (Cheng et al., 2021). Although the manufacturing industry has brought net benefits to all countries, it has also brought some environmental changes, such as the increase in the use of fossil fuels, which has worsened environmental problems and hindered sustainable development (Wu and Chang, 2020; Yang, 2021). About 70% of carbon dioxide emission is related to the production and used of products (An and Shi, 2023), therefore, the sustainable development of manufacturing industry (MI) is particularly important.

This research uses Chinese manufacturing listed firms as the data source. The importance of manufacturing to China is self-evident. It is not only the pillar industry of the national economy but also the main driving force for China's economic growth. The proportion of manufacturing industry in China's GDP has remained at around 30% for a long time, far higher than the global average. In 2022, the added value of China's manufacturing industry reached about 40.3 trillion Yuan, accounting for nearly 30% of the global manufacturing output value and firmly holding the position of the world's largest manufacturing country (World bank's World Development Indicators, 2023). However, in terms of the quality of development, most manufacturing firms still maintain a "Rough" production state, and high inputs are also accompanied by high pollution, causing serious damage to the ecological environment. To achieve the goal of "Peak Carbon and Carbon Neutrality" as soon as possible, the Chinese government has introduced a number of policies to support the transformation and upgrading of manufacturing firms, and has put forward clear requirements for the green transformation and high-quality development of the manufacturing industry (Miao and Zhao, 2023). The 2021 China Enterprise Digital Transformation Index Research Report released by Accenture shows that the average score of digital transformation of Chinese firms rose from 37 to 54 in 2018–2021, and the digitalization level of Chinese firms in various industries has shown a steady upward trend.

In the context of the economic era of rapid development of the digital economy, how digital technology and green technology could help firms to achieve the goal of sustainable development is of great significance to promote the high-quality development of China's economy and achieve the strategic goal of national sustainable development. The impact of green innovation and firm digital transformation on firm sustainable development is not explored in the existing literature, despite firms being an important micro-body of economic development. Based on literature review, this research attempts to deeply understand the framework of Digital Green Technology Innovation and provide a new measurement method and conceptual model for Digital Green Technology Innovation. According to the concept of POLE + T (Planning, Organizing, Leading, Evaluating + Technology), the framework has five dimensions. Namely Digitalization Planning, Digitalization Organizing, Green Technology Leading, Digitalization Evaluating and complementary technology (Li, 2019; Li, 2022; Robbins and Coulter, 2019).

This research analyzes the impact of digital green technology innovation on firm sustainability. This research aims to verify these relationships and further refine the dimensions of digital green technology innovation, providing a more comprehensive explanation of the path for firms to achieve sustainable development. This research uses a two-way fixed effects model to verify the relationship between variables, which is also a widely used method for panel data. This research also used instrumental variables to test the stability of the model. The heterogeneity analysis also revealed the impact of the size of a firm's profitability on the relationship between variables. Improving the profitability of firms can provide strong support for digital green technology innovation, which is more conducive to promoting firm sustainability.

2. Literature review and hypothesis development

The POLE theory includes planning, organizing, leading, and evaluating, which are the four functions of management, i.e. to drive the operation and development of an organization through planning, organizing, leading and evaluating. These four functions could be viewed as a process in which each step builds on the others. Firms must first plan, then organize according to that plan, lead others to work towards the plan, and finally evaluate the effectiveness of the plan (Abdullah and Hartzell, 2023). The POLE theory is a comprehensive management framework that emphasizes on planning, organizing, leading, and evaluating to drive development and progress of organizations (Li, 2019). POLE theory has an important role in firm management. This research applies POLE theory to Digital Green Technology Innovation measurement dimension. The sustainable development of the firm could not be achieved without good management concepts, and Digital Green Technology Innovation might have good results under the guidance of POLE theory. In addition, Complementary Technology is very important for the digital transformation and green innovation of the firm. It is a means of innovation and transformation that could help the firm to break the traditional thinking patterns and open new business areas. Therefore, the Digital Green Technology Innovation measurement dimension is added with the "T".

By promoting firm digitization as a crucial internal technological change, it offers reliable support for sustainable development. This promotion aids firms in enhancing their production processes, increasing resource utilization efficiency, and elevating the level of green competitiveness (Mubarak et al., 2021). Additionally, digitalization planning fosters the establishment of convenient information exchange platforms for firms, strengthening two-way communication between supply and demand sides of information, which leads to improved efficiency and resource utilization, thereby promoting firm sustainability (Shen and Tan, 2022).

In today's competitive market environment, digitalization organizing has emerged as a critical factor for business success. Through digitalization organizing, firms could stimulate employee creativity and engagement, enhance work efficiency and quality, bolster organizational adaptability and innovation, thereby gaining a competitive edge (Chen, 2020). Digital technologies offer organizations greater adaptability to market demands, improved work efficiency, optimized business processes, reduced costs, and drive innovation and transformation. Therefore, digitalization organizing holds significant importance for the future development of firms. With sustainability increasingly on the agenda for scholars, Digitalization organizing could support the development of globally-oriented actions, with its impact on firm sustainability becoming increasingly evident in the context of sustainable development (Bohn et al., 2023).

Green technology leading serves as a vital catalyst for fostering green technological change within organizations, which is crucial for achieving sustainable development (Deng et al., 2021). This approach emphasizes the role of leaders who prioritize environmental stewardship and innovation, driving their firms toward more sustainable practices. As highlighted by Singh et al. (2020), green technology leading has both direct and indirect effects on environmental performance, ultimately influencing a firm's overall sustainability outcomes.

In today's business landscape, Digitalization evaluating is indispensable for ensuring successful business development. Assessing the effectiveness and value of digital transformation is key to its success (Ivancic et al., 2019). Through a scientific, objective, and comprehensive evaluation approach, firms could better discern the direction and priorities of their digital transformation journey, ultimately achieving sustainable development (Zhou and Zhou, 2022).

Complementary technology serves as a catalyst for innovation and transformation, enabling firms to break free from traditional mindsets and explore new business avenues. It fosters internal cultural change, sparks employee innovation, and promotes sustainable firm development. Assistive technology for digital transformation drives innovation in technology, management, and business models. The innovation enhances market insights, profitability, productivity, and resource utilization, ultimately bolstering firm sustainability (Seman, 2019).

Hence, the hypotheses are elaborated as follows:

Hypothesis 1a: Digitalization Planning has a positive association with Firm Sustainability.

Hypothesis 2a: Digitalization Organizing has a positive association with Firm Sustainability.

Hypothesis 3a: Green Technology Leading has a positive association with Firm Sustainability.

Hypothesis 4a: Digitalization Evaluating has a positive association with Firm Sustainability.

Hypothesis 5a: Complementary Technology has a positive association with Firm Sustainability.

3. Empirical analysis

3.1. Population and sample

Chinese manufacturing listed firms are chosen as the data source to investigate the empirical research. The population in this research was 3637 Chinese manufacturing listed firms that are acquired from the database list of the China National Bureau of Statistics (CNBS) (China Statistical Yearbook, 2023). According to the large size of the population, this research is necessary to access the actual sample size as representative of all population.

The Yamane's formula is used to calculate sample size because it provides a simple and effective method for dealing with finite populations, particularly suitable for secondary data in research. The Yamane's formula can help researchers determine the required sample size to ensure the representativeness of the results, while avoiding oversampling or under sampling (Adam, 2020). Then, Yamane's formulation is used to calculate sample sizes with a 95% confidence level and e = 0.05 (Yamane, 1973). When one knows the size of the population, the sample size was determined, based on the formula as follows:

$$n = N/(1 + N(e2))$$

n = sample size;
N = population size;
e = level of precision.
The values were set for the formula:

$$N = 3637$$

$$e = 0.05$$

$$n = 3637/(1 + (3637\ (0.052)) \approx 360$$

Therefore, the sample size is at least 360 manufacturing firms, and to ensure sufficient sample data, this research selects 400 Chinese A-share listed firms. According to the requirements of Hsiao (2022) on panel data analysis, the number of cross-sectional units should be no less than 20 and the length of time series should be no less than 5 periods. The sample of this research contains 400 firms and 9 years of data. Therefore, the sample size of this research is 400 firms × 9 years = 3600 observations, which fully satisfies the minimum sample size requirement for panel data analysis.

3.2. Data collection

The data in this research adopts relevant data from secondary sources, Su (2022) found that case studies could be carried out through secondary data and information on the premise of ensuring the scientific and standardized nature of case studies.

In 2014, China initiated a significant shift toward digital transformation, propelled by the release of several key policy documents aimed at promoting digitalization across industries. This marked the beginning of a nationwide wave of digital transformation that would go on to reshape various sectors of the Chinese economy. According to Lyu et al. (2024), this period is widely recognized as a turning point for China's efforts in embracing digital technologies.

To maintain consistency and avoid the pitfalls of data discontinuity or inaccuracies due to missing data, this research focuses on China's A-share listed companies within the manufacturing sector between 2014 and 2022. The choice of this timeframe ensures that the analysis captures the full scope of the digital transformation process as it unfolded during this critical period. The main source of firm-level information and financial data is the China Stock Market and Accounting Research (CSMAR) database, a comprehensive and widely-used resource for Chinese financial data.

To refine the research sample, companies that received Special Treatment (ST) status at any point during the 2014–2022 period were excluded. ST status typically indicates financial distress or other significant operational challenges, which could skew the analysis. Additionally, companies with incomplete financial data were also excluded to ensure the robustness and reliability of the research's findings.

Then, use random sampling method for sampling. To ensure unbiased sample selection, this research used the RAND random function in EXCEL, resulting in a final dataset of 400 listed manufacturing firms (Bobbitt, 2021). This sample size provides a sufficient representation of the sector, ensuring that the research's conclusions can be generalized to a broader context within China's manufacturing industry. By focusing on this specific sector and time frame, the research aims to provide valuable insights into the impacts of digital transformation on corporate performance and strategic shifts within the manufacturing industry.

3.3. Measurements

The dependent variable of this research is Firm Sustainability, and the independent variables include Digitalization Planning, Digitalization Organizing, Green Technology Leading, Digitalization Evaluating and Complementary Technology. Firm Size and Firm Type are control variables.

Firm Sustainability—This thesis draws on the research of Khan et al. (2022), which used an independent rating agency (HEXUN-RKS) to evaluate long-term sustainability performance. Firm Sustainable performance reflects a firm is sustainable, social, environmental, and economic performance as measured by its participation in CSR-related activities in any given year. These are continuous variables from the HEXUN database, ranging from 0 (lowest rating score) to 100 (highest rating score).

Digitalization Planning—This research argues that digitalization planning mainly involves management and is divided into five dimensions, namely, management's digital job setting, management's digital orientation foresight, management's digital innovation orientation persistence, management's digital innovation orientation breadth, and management's digital innovation orientation intensity, and the weighted results of the five dimensions are used as indicators of digitalization planning. This indicator is sourced from the CSMAR database (Wu et al., 2021).

Digitalization Organizing—Digitalization Organizing indicator is divided into four dimensions, digital capital investment plan, digital human investment plan, digital infrastructure construction and science and technology innovation base construction, the result of weighting the four dimensions is used as Digitalization Organization indicator. This indicator is sourced from the CSMAR database (Wu et al., 2021).

Green Technology Leading—Green Technology Leading is measured by the financial text data platform of Wingo, and the keyword word list of environmental attention is constructed first. The keywords related to environmental issues in the CSR reports of the sample companies from 2014 to 2022 are counted, and the ratio of the word frequency of these keywords to the total word frequency is used as a proxy variable for Green Technology Leading (Wu and Hua, 2021).

Digitalization Evaluating—The Digitalization Evaluating metric is divided into three dimensions: technology innovation, business innovation and process innovation, and the result of weighting the three dimensions is used as the Digitalization Evaluation metric, which is sourced from the CSMAR database. (Wu et al., 2021).

Complementary Technology—The Complementary Technology metric is divided into four dimensions, such as Artificial Intelligence Technology, Blockchain Technology, Cloud Computing Technology and Big Data Technology, and the result of weighting the four dimensions is the Complementary Technology metric, which is sourced from the CSMAR database. (Wu et al., 2021).

Firm Size—Represents the size of the total assets available to the firm. Larger firms have more capital and could provide support for firm sustainability (Tian and Tian, 2021). In this research the natural logarithm of total assets is used to measure Firm Size (Kang and Eum, 2022). These data are sourced from the financial statements of listed companies.

Firm Type—This refers to whether the firm is state-owned. In this research, "1" is used to assign a value if it is a state-owned firm and "0" if it is not a state-owned firm (Xiao et al., 2021). These data are sourced from Statistics from the China Administration for Industry and Commerce.

3.4. Regression model

This research constructs an econometric model for two-way fixed effects regression by considering firms' individual fixed effects and time fixed effects, as well as the impact of unobservable in the control on the empirical results. The baseline econometric equations are as follows:

$$FSUit = a1 + \beta1Dipit + \beta2Dioit + \beta3Greit + \beta4Dieit + \beta5Comit + \varkappa1Sizit + \varkappa2Typit + Ui1 + Yt1 + \varepsilon it1 \quad (1)$$

where,

FSU → is Firm Sustainability;
DIP → is Digitalization Planning;
DIO → is Digitalization Organizing;
GRE → is Green Technology Leading;
DIE → is Digitalization Evaluation;
COM → is Complementary Technology;
SiZ → is Firm Size;
TYP → is Firm Type;
i → is Companies;
t → is year;

Ui → is firm individual fixed effects;

ϒt → is year fixed effects;

εit → stands for random disturbance term.

4. Results

Firstly, the research presents the correlation analysis and stationarity test to assess the reliability and applicability of the data. Secondly, the hypothesis testing and results are detailed. Finally, robustness tests and heterogeneity analysis were conducted on the model.

4.1. Correlation analysis

Table 1 demonstrates the correlation among each dimension of digital green technology innovation and firm sustainability. Digitalization planning has a significant correlation to firm sustainability ($p < 0.01$). Digitalization Organizing has a significant correlation with firm sustainability ($p < 0.01$). Green technology leading does not significantly correlate with firm sustainability (p > 0.1). Digitalization evaluating has a significant correlation to firm sustainability ($p < 0.01$). Complementary technology has a significant correlation to firm sustainability ($p < 0.01$). **Table 1** reveals that all inter-correlations do not exceed 0.80, as suggested by Hair et al. (2021), which proves that there is no multicollinearity problem among all variables. In addition, **Table 1** shows that the maximum value of VIF is 1.63, which does not exceed 10 on the scale (Gokmen et al., 2021), which indicates that there is no multicollinearity problem between the dimensions of the independent variables.

Table 1. Descriptive Statistics and correlation matrix of each dimension of digital green technology innovation and firm sustainability.

Variable	FSU	DIP	DIO	GRE	DIE	COM	VIF
Mean	21.88	49.82	24.70	2.03	37.40	35.48	
SD	14.57	22.32	6.22	0.64	17.87	15.11	
FSU	1						
DIP	0.139***	1					1.34
DIO	0.168***	0.261***	1				1.19
GRE	0.037**	−0.162***	−0.063***	1			1.08
DIE	0.205***	0.379***	0.315***	−0.100***	1		1.55
COM	0.191***	0.425***	0.340***	−0.125***	0.560***	1	1.63
TYP	0.048	−0.077	0.062	0.119	−0.023	−0.013	1.11
SIZ	0.200	0.185	0.151	0.152	0.170	0.148	1.19

Note: ** $p < 0.05$, *** $p < 0.01$.

4.2. Stationarity test

The panel unit root test is more powerful in panel data structures (Marimuthu et al., 2021). The most effective stationarity test in panel data settings is the Levin Lin Chu (LLC) test (Baltagi, 2021). Therefore, this research uses LLC to perform panel unit root tests. **Table 2** shows that at a significance level of 5% ($p < 0.05$), all LLC tests rejected the null hypotheses of panel data having unit roots. It means that all variables are stationary. Therefore, the panel data meets the requirement of stationarity.

Table 2. Stationarity test results of variables.

Variable	LLC	Result
FSU	−14.0657*** (0.0000)	Stationary
DIP	−16.2355*** (0.0000)	Stationary
DIO	−24.7932*** (0.0000)	Stationary
GRE	−15.5475*** (0.0000)	Stationary
DIE	−16.6976*** (0.0000)	Stationary
COM	−14.2391*** (0.0000)	Stationary

Note: p-value in parentheses *** $p < 0.01$.

4.3. Model construction and regression analysis

Table 3 is the result of estimates for measurement Equation (1) using mixed OLS, random effect, and fixed effect estimates, respectively. The results of the F statistical test ($p < 0.01$) suggest choosing the estimates for the fixed-effect model (FEM) over the mixed-OLS regression model (OLS). The Hausman-test results ($p < 0.01$) suggest choosing the estimates of the fixed effect model (FEM) over the random effect model (REM). The Lagrangian multiplier-test results ($p < 0.01$) suggest choosing the estimates of the random effect mode (REM) over the mixed-OLS regression model (OLS). In conclusion, the estimated results of the fixed-effect model are based on the research.

Table 3 reveals the hypothesis testing results. Firstly, the regression coefficient of digitalization planning is 0.23439, indicating that adding one unit to digitalization planning will correspondingly increase the firm sustainability by 0.23439. Digitalization planning has a strong positive significant relationship with firm sustainability (H1d: $\beta 16 = 0.23439$, $p < 0.01$). As such, the prior research (Shen and Tan, 2022) recommends that digitalization planning fosters the establishment of convenient information exchange platforms for firms, strengthening two-way communication between supply and demand sides of information. It leads to improved efficiency and resource utilization, thereby promoting firm sustainability. Hence, hypothesis 1a is supported.

Secondly, the regression coefficient of digitalization organization is 0.16545, indicating that adding one unit to digitalization organization will correspondingly increase the firm sustainability by 0.16545. Digitalization organization has a significant relationship with firm sustainability (H2d: $\beta 17 = 0.16545$, $p < 0.01$). According to previous research (Bohn et al., 2023), digitalization organizing is critical for firms' future development. With sustainability increasingly on the agenda for scholars, digitalization organizing could support the development of globally-oriented actions, with its impact on firm sustainability becoming increasingly evident in the context of sustainable development. Hence, hypothesis 2a is supported.

Table 3. Results of model construction and regression analysis for the relationships between each dimension of digital green technology innovation and firm sustainability.

FSU	**Model 10**	**Model 11**	**Model 12**
	OLS	**REM**	**FEM**
DIP	0.04565***	0.06525***	0.23439***
	(0.01165)	(0.01539)	(0.01936)
DIO	0.10635***	0.19415***	0.16545***
	(0.03899)	(0.03929)	(0.03807)
GRE	1.70582***	0.88934**	1.39103***
	(0.37094)	(0.43020)	(0.48609)
DIE	0.09648***	0.11328***	0.14268***
	(0.01556)	(0.01649)	(0.01641)
COM	0.03088	0.14833***	0.13693***
	(0.01900)	(0.02137)	(0.02232)
SIZ	2.47256	−0.35394	0.56858
	(0.21010)	(0.32274)	(0.66144)
TYP	−0.32390	1.20510	−1.57814
	(0.47983)	(0.81220)	(1.59638)
_cons	−44.54347	10.06023	−15.10186
	(4.51636)	(7.03824)	(14.56704)
Time-fixed effect	YES		YES
Entity-fixed effect			YES
F-test value	5.58***		5.58***
Hausman-test value		254.97***	
Lagrangian Multiplier-test	1040.33***		
Observations	3600	3600	3600
Adj R-squared	0.1619	0.1053	0.2191

Note: ** $p < 0.05$, *** $p < 0.01$; the parentheses indicate the robust standard error; No. of Observations = 400 companies × 9 years.

Thirdly, the regression coefficient of green technology leading is 1.39103, indicating that adding one unit to green technology leading will correspondingly increase the firm sustainability by 1.39103. The relationship between green technology leading and firm sustainability has a strong positive significant effect (H3d: $\beta 18 = 1.39103$, $p < 0.01$). Consistent with previous research (Deng, Wang, and Zhou, 2021), green technology leading serves as a driving force to propel green technological change within firms, which is critical for achieving sustainable development. As noted by Singh et al. (2020), green technology leading directly and indirectly influences environmental performance and consequently impacts firm sustainability. Hence, hypothesis 3a is supported.

Fourthly, the regression coefficient of digitalization evaluating is 0.14268, indicating that adding one unit to digitalization evaluating will correspondingly increase the firm sustainability by 0.14268. Digitalization evaluating has a significant positive influence on firm sustainability (H4d: $\beta 19 = 0.14268$, $p < 0.01$). Consistent with prior research (Zhou and Zhou, 2022), digitalization evaluating serves as an essential tool for firms to gain insights into the current state and future trajectory of the digital transformation efforts. Through a scientific, objective, and comprehensive evaluation approach, firms could better discern the direction and priorities of their digital transformation journey, ultimately achieving sustainable development. Hence, hypothesis 4a is supported.

Lastly, the regression coefficient of complementary technology is 0.13693, indicating that adding one unit to complementary technology will correspondingly increase the firm sustainability by 0.13693. The relationship between complementary technology and firm sustainability has a significant positive effect (H5d: $\beta 20 = 0.13693$, $p < 0.01$). As such, the prior research (Seman, 2019) recommends that complementary technology for digital transformation drives innovation in technology, management, and business models. The innovation enhances market insights, profitability, productivity, and resource utilization, ultimately bolstering firm sustainability. Hence, hypothesis 5a is supported.

4.4. Robustness test

To ensure the reliability of the above test results, this research has added robustness testing. The robustness test is a very important method of data analysis that could effectively avoid the interference of data outliers on the research conclusions and improve data analysis accuracy and reliability (Yang et al., 2023). Because of the backwards causality between different aspects of digital green technology innovation and firm sustainability, which could cause endogeneity problems, this research uses the instrumental variable method to process the problem. The reason for choosing Mobile Base Station Density (MBSD) as the instrumental variable in the research is that high-density mobile base station networks provide strong communication infrastructure support for firms, greatly promoting their digital transformation process, meeting the requirements of the instrumental variable method. MBSD has no direct correlation with firm sustainability meeting the exogenous requirements of instrumental variable method (Li et al., 2024). The results are shown in **Table 4**.

In the first-stage of regression, the results showed a significant correlation between MBSD and digitalization planning ($p < 0.01$). The under-identification test (LM statistic = 23.72, $p < 0.01$) and the wear identification test (F statistic = 7.66, Cragg-Donald Wald F statistic = 21.15 > 10% maximal IV size) were both significant. In the two-stage regression, the results indicate that after using the instrumental variable method, digitalization planning still positively stimulate firm sustainability, and the test results support hypothesis 1a of the previous research. Similarly, digitalization organizing, digitalization evaluating, and complementary technology have all passed the first and second stages of testing. The results ($p < 0.01$) indicate that after using the instrumental variable method, digitalization organizing, digitalization evaluating, and complementary technology still positively stimulate firm sustainability, and the test results support hypotheses 2a, 4a and 5d of the previous research. But green technology leading did not pass the wear identification test.

This research chose another instrumental variable, Government Research and Development Subsidies (GRDS), because GRDS, as an instrumental variable for green technology leading, fails the weak identification test. The rationale of selecting this instrumental variable is because the GRDS fulfils the objectives of the instrumental variable technique by offering the funding required to investigate green technology, such as novel materials that are friendly to the environment and energy-saving innovative processes. GRDS and firm sustainability that satisfies the exogenous conditions of the instrumental variable technique are not directly correlated (Qi et al., 2021). In the first-stage of regression, the results showed a significant correlation between GSUB and green technology leading ($p < 0.01$). The under-identification test (LM statistic = 36.34, $p < 0.01$) and the wear identification test (F statistic = 2.76, Cragg-Donald Wald F statistic = 36.34 > 10% maximal IV size) were both significant. In the two-stage regression, the results ($p < 0.01$) indicate that after using the instrumental variable method, green technology leading still positively stimulate firm sustainability, and the test results support hypothesis 3a of the previous research.

Table 4. Robustness test results.

	(1)	**(2)**	**(3)**	**(4)**	**(5)**
	MBSD	**MBSD**	**GRDS**	**MBSD**	**MBSD**
DIP	1.8429*** (0.3943)				
DIO		0.9718*** (0.1290)			
GRE			12.7241*** (4.8856)		
DIE				0.9745*** (0.1622)	
COM					1.1575*** (0.1822)
SIZ	−4.9091 (1.8767)	1.0601 (0.6992)	2.3069 (0.7042)	0.4732 (0.9031)	−0.2592 (0.8972)
TYP	−4.1649 (2.7483)	−1.6376 (1.6591)	−3.7272 (1.9705)	1.7374 (2.1350)	−1.9793 (1.9706)
_cons	83.9337 (33.2189)	−7.3134 (16.2659)	−49.4656 (22.1924)	−23.1751 (20.4831)	1.2285 (19.3844)
Time-fixed effect	YES	YES	YES	YES	YES
Entity-fixed effect	YES	YES	YES	YES	YES
Adj R-squared	0.5192	0.8149	0.8038	0.7088	0.7396
Observations	3600	3600	3600	3600	3600
First stage					
Iv1 (MBSD)	0.2168*** (0.0471)	0.4112*** (0.0233)		0.4101*** (0.0620)	0.3452*** (0.0455)

Table 4. (*Continued*).

	(1)	(2)	(3)	(4)	(5)
	MBSD	**MBSD**	**GRDS**	**MBSD**	**MBSD**
Iv2 (GRDS)			0.0192*** (0.0032)		
LM statistic	23.72 [0.00]	319.94 [0.00]	36.34 [0.00]	48.70 [0.00]	63.73 [0.00]
F statistic	7.66 {21.15}	8.38 {311.06}	2.76 {36.34}	7.74 {43.73}	7.68 {57.47}

Note: ** $p < 0.05$, *** $p < 0.01$; No. of Observations = 400 companies × 9 years; the parentheses indicate the robust standard error; the *p*-value is in square brackets; the critical value corresponding to the 10% level of the Stock-Logo test is indicated in curly braces.

4.5. Heterogeneity analysis

Heterogeneity analysis was used in this research to assess and distinguish the variations among several investigations and ensure the validity and dependability of the research findings (Johnson and Johnson, 2020).

Firm profitability is an important indicator for measuring business performance and a crucial factor affecting whether a firm could adopt digital green technology. A firm's strong profitability indicates that it has a robust economic foundation and sufficient funds to invest in technological innovation, thereby promoting firm sustainability. To verify whether there is heterogeneity in the impact of digital green technology innovation on firm sustainability, this research divided the research sample based on the median return on assets (ROA) (Hamid and Chowdhury, 2021). Firms with a ROA above the median are classified as strong profitability firms, while those with a ROA below the median are classified as weak profitability firms. The results of the heterogeneity analysis in **Table 5**'s columns 2 and 3 show that digitalization organizing, green technology leading, and complementary technology are much more important when profitability is high than when it is low. For high-profitability companies, the corresponding firm sustainability rises by 0.1734 for each extra unit of digitalization organizing. Firm sustainability rises by 1.7814 for each unit of green technology leadership. Additional units of complementary technology result in a 0.1913 rise in firm sustainability. For businesses with low profitability, the associated firm sustainability rises by 0.1200 for every unit of digitalization organizing. Green technology has little effect on a company's ability to remain sustainable. Additional units of complementary technology result in a 0.0698 rise in firm sustainability. It indicates that there is indeed heterogeneity in the impact of digital green technology innovation (digitalization organizing, green technology leading, and complementary technology) on firm sustainability. One possible explanation could be that companies with strong profitability often overlook financial pressures when implementing digitalization, green technology leading, and complementary technology, which could help to better coordinate firm resources and apply new technologies to promote firm sustainability.

Table 5. Heterogeneity analysis of the impact of digital green technology innovation on firm sustainability.

FSU	**Strong profitability**	**Weak profitability**
DIP	0.1943***	0.2136***
	(0.0303)	(0.0290)
DIO	**0.1734*** **	**0.1200** **
	(0.0491)	(0.0596)
GRE	**1.7814** **	**0.8991**
	(0.6993)	(0.7039)
DIE	0.1360***	0.0852***
	(0.0232)	(0.0242)
COM	**0.1913*** **	**0.0698** **
	(0.0314)	(0.0324)
SIZ	0.8816	−0.5056
	(1.0345)	(1.0283)
TYP	0.1727	−2.1457
	(2.4446)	(2.3024)
_cons	−21.1972	12.6964
	(23.3554)	(22.1040)
Time-fixed effect	YES	YES
Entity-fixed effect	YES	YES
N	1969	1631
Adj *R*-squared	0.1839	0.0358

Note: ** $p < 0.05$, *** $p < 0.01$; the parentheses indicate the robust standard error.

5. Discussion

This research investigates the relationship between digital green technology innovation and firm sustainability in the manufacturing industry of Chinese listed companies. This research follows the previously proposed role of digital technology in promoting firm sustainability, as well as the conditions created by green technology for firm sustainability. This research proposes a new variable: digital green technology innovation. The dimension of this variable is based on previous research on digital technology and green innovation, and combined with the theoretical analysis framework proposed by POLE theory. The results indicate that all dimensions of digital green technology innovation can promote the sustainable development of companies.

This empirical study proposes two suggestions for companies to achieve sustainable development. Firstly, adding one unit to digitalization planning will correspondingly increase the firm sustainability by 0.23439. Firms should use digitalization planning to modify their production and operation methods, organize various resources, and improve the market innovation and entrepreneurial environment. Simultaneously, firms should utilize complementary technology to accelerate digital transformation, accurately assess resource consumption and environmental impact in the production process, optimize resource allocation, improve resource efficiency, reduce environmental costs. This would promote technological innovation in firms, reduce pollution and environmental damage, and affect the firm sustainability. Next, adding one unit to digitalization organization will correspondingly increase the firm sustainability by 0.16545. Digital organizing involves setting up robust plans for digital capital investment, human resource allocation, and building necessary digital infrastructure, all of which support the integration of green technologies. Adding one unit to green technology leading will correspondingly increase the firm sustainability by 1.39103. The leadership's dedication to Green Technology Leading is crucial, as it guarantees the prioritization of environmental values at the management level, thereby fostering a corporate culture that prioritizes sustainability. Moreover, adding one unit to digitalization evaluating will correspondingly increase the firm sustainability by 0.14268. Through digital evaluation, firms should continuously assess innovations in technology, processes, and business models to refine and optimize their sustainability strategies. Finally, adding one unit to complementary technology will correspondingly increase the firm sustainability by 0.13693. Leveraging complementary technologies like AI, blockchain, cloud computing, and big data will allow firms to streamline operations, reduce resource waste, and make more informed, environmentally responsible decisions. By addressing these five dimensions, companies can achieve long-term sustainability while maintaining competitive advantage.

Secondly, the profitability of firms has a significant impact on the relationship between digital green technology innovation and firm sustainability. Firms that want to be highly profitable should improve their cost control, invest more in R&D, and open up new sales channels. For instance, companies can learn more about their operating costs and pinpoint areas for cost reduction by employing data analytics solutions. Businesses can estimate future expenses, monitor spending trends, and allocate funds wisely thanks to advanced analytics. An increase in a company's profitability would strengthen its financial base and offer robust backing for the development of digital green technologies. Additionally, this is a good way to support the company's long-term growth. Even when funding is scarce, low-profitability businesses should find ways to raise money for technological research and development, perhaps through government grants, collaborative R&D, and other ways to ease financial strain. Simultaneously, improve internal training, actively introduce talent with digital and green innovation concepts, and raise employees' awareness and proficiency in innovation. Form collaborative partnerships with research organizations to conduct technical innovation and research together, share resources, and reap complementary benefits.

This research only studies the impact of digital green technology innovation in the manufacturing industry on the firm sustainability. Digital green technology innovation involves many industries, and the research content will be expanded to other industries in the future, such as finance and retail trade. These industries are also facing challenges such as green management, improving environmental benefits, and technological innovation. This research extends the model to other industries and explores new models of green digital innovation. This research has the potential to further conduct heterogeneity analysis, expand to other countries, and investigate the impact of digital green technology innovation on firm sustainability in various industries, as well as the impact of digital green technology innovation in other countries on firm sustainability. Further analysis of the specific reasons could make this research more universal and enhance its practical value. Future research will focus on the role of supply chain relationships, green management innovation, and green total factor productivity as mediating variables in the relationship between digital green technology innovation and firm sustainability. This future research will also add some moderating variables to make the research more comprehensive.

Author contributions: Conceptualization, ZJ and SB; methodology, ZJ and SB; validation, SB and JP; formal analysis, ZJ; resources, JP; data curation, ZJ; writing—original draft preparation, ZJ; writing—review and editing, SB; visualization, ZJ; supervision, SB; project administration, SB; All authors have read and agreed to the published version of the manuscript.

Acknowledgments: This research project was financially supported by Mahasarakham Business School, Mahasarakham University.

Conflict of interest: The authors declare no conflict of interest.

References

Abdullah, Y., and Hartzell, S. (2023). Function of Management-Definition & Roles. Study.com, retrieved March 1, 2024. www.study.com.

Abubakr, M., Abbas, A. T., Tomaz, I., Soliman, M. S., Luqman, M., and Hegab, H. (2020). Sustainable and Smart Manufacturing: An Integrated Approach. Sustainability, 12 (6), 2280.

Adam, A. M. (2020). Sample size determination in survey research. Journal of Scientific Research and Reports, 26(5), 90–97.

Ali, B. J., and Anwar, G. (2021). An empirical study of employees' motivation and its influence job satisfaction. International Journal of Engineering, Business and Management, 5(2), 21–30.

Alsayegh, M. F., Rahman, R. A., and Homayoun, S. (2020). Corporate Economic, Environmental, and Social Sustainability Performance Transformation through ESG Disclosure. Sustainability, 12(9), 3910.

An, Q. G., and Shi, Y. S. (2023). Does enterprise digitization reduce carbon emissions? Evidence from China. Chinese Journal of Population Resources and Environment, 21(4), 219–230.

Baltagi, B. H. (2021). Econometric Analysis of Panel Data. Springer Nature: Cham, Switzerland. (6), 1–424.

Bobbitt, Z. (2021). How to perform systematic sampling in Excel (Step-by-step). https://www.statology.org.

Bohn, S., Gümüsay, A. A., von Richthofen, G., and Reischauer, G. (2023). Digital organising. Internet Policy Review, 12(4).

Chen, J. (2020). The impact of organizational empowerment on employee creativity and participation: Evidence from China. Journal of Business Research, 112, 1–10.

Cheng, L., Guo, W., Cao, X., Dou, Y., Huang, L., Song, Y., Su, J., Zeng, Z., and Ye, R. (2021). Laser-induced graphene for environmental applications: progress and opportunities. Progress in Physics and Chemistry of Materials, 11(1), 1–24.

China National Bureau of Statistics (NBS). (2023). China Statistical Yearbook.

Deng, Y. P., Wang, L., and Zhou, W. J. (2021). Do environmental regulations promote green innovation capacity? —Empirical evidence from China. Statistical Research, 38(7), 76–86.

Gao, S., Meng, F., Gu, Z., Liu, Z., and Farrukh, M. (2021). Mapping and clustering analysis on environmental, social and governance field a bibliometric analysis using scopus. Sustainability, 13(13), 7304.

Hamid, M. A., and Chowdhury, M. A. H. (2021). Profitability, capital structure, and firm performance: Evidence from emerging markets. Journal of International Financial Markets, Institutions and Money, 72, 101282.

Hsiao, C. (2022). Analysis of panel data (4th ed.). Cambridge University Press. https://doi.org/10.1017/9781009057745.

Ivancic, L., Vuksic, V. B., and Spremic, M. (2019). Mastering the digital transformation process: Business practices and lessons learned. Technology Innovation Management Review, 9 (2), 6 – 50.

Johnson, J. D., and Johnson, R. B. (2020). Corporate governance, firm performance, and profitability: Evidence from the UK. Journal of Business Research, 116, 245–257.

Kang, T., and Eum, W. (2022). Relationship Between Firm Size and Firm Growth: Evidence from Korean Manufacturing Firms. Singapore Economic Review, 1–24.

Khan, M. K., Naeem, K., and Xie, M. Y. (2022). Does managerial ability transform organization from the inside out? Evidence from sustainability performance of financially constrained firms in an emerging economy. Borsa Istanbul Review, 22(5), 897–910.

Lee, C. C., and Lee, C. C. (2022). How does green finance affect green total factor productivity? Evidence from China. Energy Economics, 107, 105863.

Li, J. K., Ji, L. Y., Zhang, S., and Zhu, Y. P. (2024). Digital technology, green innovation, and the carbon performance of manufacturing enterprises. Environmental Science and Pollution Research. 30 (29), 74409–74425.

Li, N. (2019). Research on the application of POLE concept in teaching management of universities. Science and Technology Information, (19), 174–175.

Li, Y. J. (2022). Theoretical Logic, Practical Dilemmas and International Experiences of Digital Transformation of Small and Medium-sized Enterprises. People’s Forum on Academic Frontiers, 18, 37–51.

Lyu, X. C., Pang, Z., and Xu, Y. Y. (2024). Has the digital transformation promoted energy-saving-biased technological progress in China’s manufacturing sector? Applied Economics.

Marimuthu, M., Khan, H., and Bangash, R. (2021). Is the Fiscal Deficit of ASEAN Alarming? Evidence from Fiscal Deficit Consequences and Contribution towards Sustainable Economic Growth. Sustainability. 13(18).

Miao, Z. Y., and Zhao, G. H. (2023). Confgurational paths to the green transformation of Chinese manufacturing enterprises: a TOE framework based on the fsQCA and NCA approaches. Scientifc Reports, 13, 19181.

Mubarak, A., Song, D., and Zhu, W. (2021). Can firm digitalization promote green technological innovation? An examination based on listed companies in heavy pollution industries. Journal of Finance and Economics, 48(4), 34–48.

Qi, M., Yang, S., Nnenna, A. B., and Li, W. (2021). Environmental regulation, government subsidies, and green technology innovation—A provincial panel data analysis from China. International Journal of Environmental Research and Public Health, 18(22), 11991.

Robbins, S., and Coulter, M. (2019). Principles of Management. China Machine Press.

Seman, N. A. A. (2019). The mediating effect of green innovation on the relationship between green supply chain management and environmental performance. Journal of Cleaner Production, 229, 115–127.

Shen, M., and Tan, W. (2022). Digitalisation and corporate green innovation performance-Identifying dual effects based on incremental and qualitative improvement. Southern Economy, (9), 118–138.

Silva, F. (2023). Sustentabilidade empresarial e ESG: uma distinção imperativa. Revista De Gestao e Secretariado, 14(1), 247–258.

Singh, S. K., Del Giudice, M., Chierici, R., and Graziano, D. (2020). Green innovation and environmental performance: The role of green transformational leadership and green human resource management. Technological Forecasting and Social Change, 150, 119762.

Su, J. Q. (2022). Mechanisms of digital capability evolution in the context of continuous digital transformation-based on a resource orchestration perspective. Scientific Research, 40(10), 1853–1863.

Tian, H., and Tian, J. H. (2021). The mediating role of responsible innovation in the relationship between stakeholder pressure and corporate sustainability performance in times of crisis: Evidence from selected regions in China. International Journal of Environmental Research and Public Health, 18(14), 1–17.

World Bank. (2023). World development indicators. Retrieved from https://data.worldbank.org.cn/indicator/nv.ind.manf.kd.zg?locations=cn.

Wu, F., Hu, H. Z., and Lin, H. Y. (2021). Corporate Digital Transformation and Capital Market Performance-Empirical Evidence from Equity Liquidity. World of Management, 21(7), 130–140.

Wu, J. Z., and Hua, X. Y. (2021). Executive Team Attention and Corporate Green Innovation Strategy-Empirical Evidence from Listed Chinese Manufacturing Companies. Science of Science and Management of S &T, 42(9), 122–142.

Wu, W. W., and Chang, X. X. (2020). Does Environmental Regulation Affect Business Performance? --Taking A-share Listed Companies in Heavy Pollution Industry as an Example. Journal of Jiangxi University of Science and Technology, 41(6), 34–40.

Xiao, H., Yang, Z., and Liu, M. (2021). The Social Responsibility Promotion Effect of Corporate Digitisation: A Test of Internal and External Dual Paths. Economic Management, (11).

Xie, X. M., and Zhu, Q. W. (2021). How to solve the problem of "harmonious symbiosis" in enterprise green innovation practice? Management World. (1), 128–149.

Yamane, T. (1973). Statistics: An Introductory Analysis. New York: Harper & Row.

Yang, Y. P., Zhao, P. X., and Huang, X. (2023). Robust variable selection for linear regression models with fixed effects under panel data. Journal of Applied Statistics and Management.

Zhao, Y. H., Su, Q., Li, B. K., Zhang, Y. Y., Wang, X. J., Zhao, H., and Guo, S. (2022). Have those countries declaring "zero carbon" or "carbon neutral" climate goals achieved carbon emissions-economic growth decoupling? Journal of Cleaner Production, 363, 132450.

Zheng, J. L. (2023). Promoting greening by digitalization: the construction of digital ecological civilization promotes the harmonious coexistence between man and nature. China News. www.chinanews.com.

Zhou, P. Y., and Zhou, S. Y. (2022). Executive Overconfidence, Digital Transformation and Environmental Innovation: The Role of Moderated Mediator. International Journal of Environmental Research and Public Health, 19(10).