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Sustainability of Innovative Digital Green Technology in Chinese Manufacturing

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ABSTRACT. Intensive environmental pressures and the global pursuit of carbon neutrality have made digitalization and green technology key drivers of sustainable development at the enterprise level, particularly in the manufacturing industry. This research examines how innovative digital green technologies influence the sustainable development of Chinese-listed manufacturing companies using the POLC+T framework (Planning, Organizing, Leading, Controlling, and Complementary Technology). It utilizes time series data from 400 Chinese A-share manufacturing companies over the period 2014–2024. The research employs the ordinary least squares (OLS) regression analysis and instrumental variable techniques to ensure reliability and address potential intra-relationship issues. The findings show that innovative digital organizing, green technological leading, and innovative digitalization controlling have significant positive impacts on firms' sustainable development, as measured by environmental, social, and governance (ESG) sustainability scores. Complementary technology such as artificial intelligence, big data, cloud computing, and blockchain show a significant mediating role, strengthening the sustainable development impacts of key digital and green innovation activities. The research suggests that sustainability outcomes are not only the result of green technology adoption but also of integrated management processes that link digital transformation with strategic environmental leadership. This research contributes to the literature by conceptualizing and empirically validating innovative digital green technology as a multidimensional framework based on management theory. In practice, the findings provide actionable insights for policymakers and managers seeking to accelerate the transformation towards sustainability in the manufacturing sector through coordinated digital and green innovation strategies. Therefore, this research enhances our understanding of how technology-driven management approaches can link economic efficiency and long-term environmental sustainability in emerging economies.

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1. Introduction

In the past decades, the development of industrialization has promoted social progress, but it has also caused some environmental consequences, such as climate change, resource shortage and environmental pollution [1]. 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 climate change [2].

The concept of environmental, social, 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 [1, 3]. The call for reducing pollution and restoring the environment has led to the adoption of international agreements such as Kyoto Protocol and Paris Climate Agreement [4, 5]. Therefore, 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 [6].

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 [7]. In recent years, green innovation and digital technology have become the keyways for the harmonious coexistence between man and nature [8].

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 [9]. 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 [10].

Manufacturing is an important pillar of the global economy because it greatly promotes economic development, creates employment opportunities and increases people's income [11]. However, manufacturing also consumes a lot of energy [12]. 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 [13]. About 70% of carbon dioxide emission is related to the production and used of products [14], 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 [15]. 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 [16]. 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 POLC+T (Planning, Organizing, Leading, Controlling, +Technology), the framework has five dimensions. Namely Innovative Digitalization Planning, Innovative Digitalization Organizing, Green Technological Leading, Innovative Digitalization Controlling and Complementary Technology [17, 18].

This research analyzes the impact of innovative digital green technology on firm sustainability. This research aims to examine these relationships and further refine the dimensions of innovative digital green technology, providing a more comprehensive explanation of the path for firms to achieve sustainable development. This research uses a regression model to examine the relationship between variables, which is also a widely used method for average time series data. This research also used instrumental variables to test the stability of the model. Improving the complementary technology of firms can provide strong support for innovative digital green technology, which is more conducive to promoting firm sustainability.

2. Literature Review and Hypothesis Development

The POLC theory includes planning, organizing, leading, and controlling, which are the four functions of management, i.e. to drive the operation and development of an organization through planning, organizing, leading, and controlling. 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 control the effectiveness of the plan [19]. The POLC theory is a comprehensive management framework that emphasizes on planning, organizing, leading, and controlling to drive development and progress of organizations [17]. POLC theory has an important role in firm management. This research applies POLC theory to Innovative Digital Green Technology measurement dimension. The sustainable development of the firm could not be achieved without good management concepts, and Innovative Digital Green Technology (IDGT) might have good results under the guidance of POLC theory. In addition, Complementary Technology is very significant 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 Innovative Digital Green Technology 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 [20]. 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 [21].

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, and strengthen the organization's adaptability and innovation, thereby gaining a competitive edge [22]. 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, innovative 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 [23].

Green technological leading serves as a key catalyst in promoting green technological change within organizations, which is critical to achieving sustainable development [24]. This approach emphasizes the role of leaders who prioritize environmental stewardship and innovation, driving their firms toward more sustainable practices. As highlighted by [25], green technological leading has both

direct and indirect effects on environmental performance, ultimately influencing a firm's overall sustainability outcomes.

Complementary technology acts as a catalyst for innovation and transformation, helping firms to break free from traditional mindsets and explore new business paths. It raises internal cultural change, sparks employee innovation, and promotes sustainable firm development. Technology supporting digital transformation drives innovation in technology, management, and business models. The innovation enhances market understanding, profitability, productivity, and resource efficiency, ultimately strengthening the firm's sustainability [26]. Complementary technology is an advanced technology-driven change that helps companies to optimize and upgrade their business processes using modern technology. This technology could cover a variety of fields, such as artificial intelligence (AI), big data, cloud computing, etc., to provide firms with more efficient and smarter solutions. Digital transformation assistive technology could help firms enhance their competitiveness and stand out in the fierce market competition by optimizing business processes, improving productivity, and reducing costs.

The business landscape, innovative digitalization controlling is indispensable for ensuring successful business development. Assessing the effectiveness and value of digital transformation is key to success [27]. 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 [28].

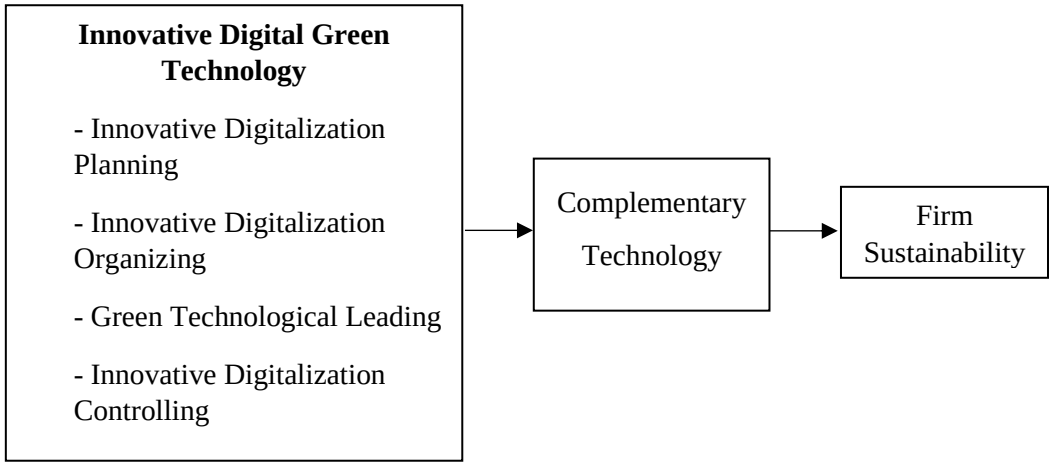

Figure 1: Conceptual Framework

Hence, the hypotheses are elaborated as follows.

Hypothesis 1: Innovative Digitalization Planning positively influences Firm Sustainability.

Hypothesis 2: Innovative Digitalization Organizing positively influences Firm Sustainability.

Hypothesis 3: Green Technological Leading positively influences Firm Sustainability.

Hypothesis 4: Innovative Digitalization Controlling positively influences Firm Sustainability.

Hypothesis 5: Complementary Technology mediates the relationship between Innovative Digitalization Planning and Firm Sustainability.

Hypothesis 6: Complementary Technology mediates the relationship between Innovative Digitalization Organizing and Firm Sustainability.

Hypothesis 7: Complementary Technology mediates the relationship between Green Technological Leading and Firm Sustainability.

Hypothesis 8: Complementary Technology mediates the relationship between Innovative Digitalization Controlling and 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 4,037 Chinese manufacturing listed firms that are acquired from the database list of the China National Bureau of Statistics (CNBS) [29]. 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 [30]. Then, Yamane's formulation is used to calculate sample sizes with a 95% confidence level and e = 0.05 [31].

When one knows the size of the population, the sample size was determined, based on the formula as follows:

$n = N/ (1+N(e^2))$

n = sample size

N = population size

e = level of precision

The values were set for the formula:

N = 4445

e = 0.05

$n = 4445 / (1+ (4445 (0.05^2)) \approx 367$

Therefore, the sample size is at least 367 manufacturing firms, and to ensure sufficient sample data, this research selects 400 Chinese A-share listed firms. According to the requirements of [32] 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 367 firms and 11 years of data. Therefore, the sample size of this research is 367 firms x 11 years = 4,037 observations, which fully

satisfies the minimum sample size requirement for analysis. After collecting all the data, the averages were calculated and then analyzed using multiple linear regression analysis.

3.2 Data Collection

The data in this research adopts relevant data from secondary sources, [33] 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 [34], 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 2024. 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 2014-2024 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 [35, 36]. 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 Innovative Digitalization Planning, Innovative Digitalization Organizing, Green Technological Leading, Innovative Digitalization Controlling and Complementary Technology.

Firm Sustainability, this research draws on the research of [35], 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).

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 [36, 37].

Innovative 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 [36, 37].

Innovative Digitalization Organizing, Innovative 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 [36, 37].

Green Technological Leading, Green Technological 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 Technological Leading [38].

Innovative Digitalization Controlling, the Innovative Digitalization Controlling 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 Control metric, which is sourced from the CSMAR database [36, 37].

3.4 Regression model

The stationarity testing is required to confirm the dependability and stationarity of data [39]. The null hypothesis that data has a unit root is rejected when all variables are at a significance level of 5% ($p < 0.05$), indicating that all variables are stationary [40]. The p-values for every variable in this research are less than 0.05, indicating that the data set is steady and appropriate for reliable data analysis.

The Ordinary Least Squares (OLS) regression analysis is employed to investigate the hypothesized relationships. The regression equation is a linear combination of the independent variables that are considered to best explain and predict the dependent variable. The results of

OLS regression analysis for H1-H8 are presented in Table 2. The baseline econometric equations are as follows:

$$MFS = a + \beta_1 IDP + \beta_2 IDO + \beta_3 GTL + \beta_4 IDC + \beta_5 MCT + \beta_6 (IDP*MCT) + \beta_7 (IDO*MCT) + \beta_8 (GTL*MCT) + \beta_9 (IDC*MCT)$$

Where:

MFS is Firm Sustainability for Chinese Manufacturing

IDP is Innovative Digitalization Planning

IDO is Innovative Digitalization Organizing

GTL is Green Technological Leading

IDC is Innovative Digitalization Controlling

MCT is Complementary Technology for Chinese Manufacturing

4. Results

4.1 Correlation analysis

Table 1 demonstrates the correlation among each dimension of innovative digital green technology and firm sustainability. Innovative digitalization planning, innovative digitalization organizing, innovative digitalization controlling, and complementary technology have a significant correlation to firm sustainability ($p < 0.01$). However, the green technological leading has no correlation to firm sustainability ($p > 0.05$). Table 1 reveals that all inter-correlations do not exceed 0.80, as suggested by [41], which proves that there is no multicollinearity problem among all variables. In addition, the maximum value of VIF is 2.04, which does not exceed 10 on the scale [40], which indicates that there is no multicollinearity problem between the dimensions of the independent variables.

Table 1. Correlation Matrix of Each Dimension of Innovative Digital Green Technology and Firm Sustainability

Variable	MFS	IDP	IDO	GTL	IDC	MCT	VIF
Mean	21.88	49.76	24.69	2.03	37.35	35.48	-
SD	8.89	19.97	3.81	0.50	12.59	11.90	-
MFS	1						-
IDP	0.152***	1					1.57
IDO	0.194***	0.439***	1				1.35
GTL	0.063	-0.295***	-0.147***	1			1.10
IDC	0.162***	0.530***	0.452***	-0.201***	1		1.52
MCT	0.136***	0.558***	0.491***	-0.196***	0.650***	1	2.04

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

4.2 Model Construction and Regression Analysis

Table 2 is the result of estimates for measurement equation using OLS. [40, 41] suggest that whether F-test is rejected the null hypothesis of a common intercept, that dataset is reliability to analyze. Most of the estimated coefficients are statistically significant. Moreover, the relationship rate is 28.90% and the F-test for model is strong significant at the 5% level. The value of Durbin-Watson found that 1.751. It confirms that values of all variables are accepted and trustworthy range from 1.50 to 2.50 [42]. The results indicate that **Hypotheses 2, 3, and 4 are supported**. The hypothesis proposes that innovative digitalization organizing, green technological leading, and innovative digitalization controlling are positively affected to firm sustainability. According to the findings, manufacturing firms' sustainability increases with their level of green technology innovation [43].

Table 2. The Results of the Regression Analysis

	Model 1	**Model 2**
Independent Variables	**coefficient**	
Constant	**-3.699*** (0.753)	**3.328*** (0.483)
Innovative Digitalization Planning (IDP)	0.696 (0.564)	0.042 (0.090)
Innovative Digitalization Organizing (IDO)	**6.564*** (2.740)	**1.012*** (0.381)
Green Technological Leading (GTL)	**7.729*** (1.898)	-3.861 (2.400)
Innovative Digitalization Controlling (IDC)	**2.284*** (0.880)	-0.053 (0.130)
IDP*MCT		0.002 (0.002)
IDO*MCT		**-0.016*** (0.007)
GTL*MCT		**0.178*** (0.063)
IDC*MCT		0.003 (0.004)
No. of Obs.	400	400
R^2	29.80%	28.10%
R^2 Adjusted	28.90%	26.20%
F-Statistic	10.670*	4.275*
Durbin-Watson	1.751	2.102

* represent statistical significance at 5%, standard errors in parentheses

According to earlier studies, the organization of digitalization encourages ongoing innovation in products and services, which leads businesses and industries to shift from production practices that harm the environment to the creation of green industries. Consequently, it encourages businesses to upgrade to greener practices and establishes a favorable funding climate for the innovation and green sectors. The result is consistent with [44]'s study, who state that the China's transition to technology- and capital-intensive industries is made possible by its digital economy, which is the integration of digital technology with production factors, driven by digitalization organizing. The change encourages businesses to go green and digital innovation. The research findings also show a substantial positive link between green technological leadership and firm sustainability. This is to approve the [45]'s study that the effect of green technology leadership may encourage the establishment of green technological innovation dimensions and the replacement of antiquated equipment with low-carbon, environmentally friendly alternatives, increasing the firm sustainability.

The Model 2 in Table 2, the Adjusted R^2 is 26.20%, the F-test for model is strong significant at the 5% level. The value of Durbin-Watson is 2.102 which is acceptable [41]. When the mediating variable like complementary technology involves into the model, the relationship between innovative digitalization organizing and green technological leading have a strong negatively and positively significant effect on firm sustainably, respectively. Even the results show the innovative digitalization organizing has a negative significant effect on firm sustainably. The innovative digitalization controlling is still not significant in the Model 2. According to [46], innovative digitalization controlling allows businesses to precisely examine resource consumption and environmental impacts during production processes, resulting in better resource allocation, increased resource efficiency, and lower environmental costs. This research finding contradicts their findings. Even [47], innovative digitalization controlling could help businesses produce more efficient and ecologically friendly technologies and goods by offering advice and recommendations for technological innovation. Thus, the **Hypotheses 6 and 7 are supported**.

5. Conclusion

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 innovative digital technology in promoting firm sustainability, as the conditions created by green technology for firm sustainability. This research proposes a new variable: innovative digital green technology. 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 POLC theory. The results indicate that all dimensions of innovative digital green technology can promote the sustainable development of companies.

This empirical study proposes two suggestions for companies to achieve sustainable development. Firstly, innovative 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. A leader's commitment to green technology is significance, as it ensures environmental values are prioritized at the management level, raising a sustainability-focused firm culture. Moreover, through innovative digital controlling, firms should continuously measure innovations in technology, processes, and business models to refine and optimize their sustainability strategies. Finally, 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 complementary technology of firms has a significant impact on the relationship between innovative digital green technology and firm sustainability. Previous research [48] suggests that these technologies, through the processing of large volumes of data, provide precise and timely insights, thereby enhancing businesses' understanding of market trends and customer preferences. Facilitates faster development and launch of new products, services, and business models, driving innovation in green management practices [49].

This research focuses only on the impact of innovative digital green technology in the manufacturing industry on the firm sustainability. Innovative digital green technology involves many industries, and the research content will be expanded to other industries in the future, such as finance and retail trade. This research has the potential to further conduct heterogeneity analysis, expand to other countries, and investigate the impact of innovative digital green technology on firm sustainability in various industries, as the impact of digital green technology innovation in other countries on firm sustainability. Further analysis of the specific reasons could make this study more comprehensive and increase 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 innovative digital green technology and firm sustainability. This future research will also add some moderating variables to make the research more comprehensive.

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