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Research on Digital Transformation and Green Technology Innovation—Evidence from China's Listed Manufacturing Enterprises

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Abstract: Green development and the digital economy are receiving increasing attention among scholars, practitioners, and policy makers, as the link between the two remains unclear, and exploring the study of the mechanisms at play between the two to achieve quality economic development is an urgent issue to be addressed. This study addresses this gap and aims to provide clarity by analyzing examples of business practices in developing countries. Using a total of 20,283 datasets from 2049 listed manufacturing firms from China from 2007 to 2020 as the study sample, the mechanism of digital transformation's impact on firms' green technological innovation capability is empirically examined and the mediating role of firms' green dynamic capabilities is verified. This study finds that: (1) Digital transformation significantly enhances the level of green technology innovation of enterprises. (2) There is a partial mediating effect of green dynamic capabilities in the process of digital transformation positively affecting enterprises' green technology innovation. (3) Digital transformation by state-owned, central and western regions and by medium-sized enterprises is more significantly effective in promoting green technology innovation than non-state-owned, eastern regions and small and large enterprises. (4) The analysis of economic consequences shows that digital transformation can mitigate the incremental costs incurred in the process of digital transformation by empowering enterprises to achieve green development and cost reduction through green technology innovation.

Keywords: digital transformation; green technology innovation; green dynamic capability; high-quality development; manufacturing

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1. Introduction

Achieving green and sustainable development has become a major global agenda. The European Union, Japan, and China have committed themselves to "carbon neutrality"; the EU has proposed a new industrial system with a greater focus on social and ecological values—Industry 5.0—which states that the manufacturing industry must respect and protect the earth and achieve sustainable development. However, the manufacturing industry is currently facing problems such as high costs and low success rates to achieve sustainable development, so it is urgent to find effective ways to develop. Green technology innovation is being initiated throughout the product manufacturing life cycle [1], emphasizing the minimization of waste of resources and energy in the entire life cycle of design, manufacturing, assembly, transportation, sales, after-sales service, and recycling of products at the end of life; striving to save energy and reduce consumption, reduce pollution and damage to the ecological environment [2]; and helping manufacturing enterprises to reduce production energy consumption, reduce waste emissions, and alleviate environmental pollution. It has become an important choice for manufacturing industries to achieve sustainable development.

Therefore, how to improve the green technology innovation of manufacturing enterprises has become a hot topic. Studies have shown that environmental laws and regulations [3,4], incentive policies such as financial subsidies [5], and green finance [6] can urge or help enterprises to engage in green technology innovation, while external stakeholders such as government support [7] and customer demand [8] can motivate enterprises to seek green technology innovation [9]. Elements such as management's green orientation [10,11], organizational capability [12,13], and organizational governance structure [14] are important factors in promoting green technology innovation.

Moreover, human society has entered the digital era and enterprises have started to apply digital technologies such as cloud computing, big data, and artificial intelligence to transform their production, operation, and business models, i.e., digital transformation [15]. While reshaping the competitiveness of enterprises, digital transformation also brings breakthroughs to enhance the green technology innovation of enterprises [16]. A study by the Global e-Sustainability Initiative (GeSI) suggests that digitalization will help reduce global CO2 emissions by 20% by 2030 by revolutionizing smart grids and integrated energy management systems. It is thus clear that digital transformation may contribute to sustainable economic and social development by enhancing green technological innovation, but there is no clear answer to its underlying mechanisms.

One of the key outcomes of digital transformation is the enhancement of the dynamic capabilities of companies [15]. Dynamic capabilities help enterprises to achieve the absorption, reconstruction, and application of external green sustainability knowledge [17], forming green dynamic capabilities. At the same time, some studies have shown that the enhancement of enterprises' green dynamic capability helps to acquire external green knowledge of the organization, enhance the efficiency of green knowledge adoption, and promote enterprises' green technological innovation [3], as well as improve enterprises' green innovation recognition ability and promote enterprises' green technological innovation [18,19]. Therefore, this study argues that digital transformation can enhance green dynamic capabilities and promote green technological innovation, and we thus construct a model for empirical testing.

From the above, this study collects relevant data at the enterprise level and constructs an econometric model for empirical testing. We examine the impact mechanism of digital transformation on enterprises' green technology innovation capability and verify the mediating role of enterprises' green dynamic capability. In addition, to deal with the endogeneity between digital transformation and green technology innovation, this study (1) adopts the instrumental variables approach and conducts a series of robustness tests; (2) further analyzes the economic consequences of digital transformation to enhance enterprises' green technology innovation capability; and finally (3) explores the heterogeneity of the impact of digital transformation on enterprises' green technology innovation for enterprises with different characteristics, with the following main contributions: discovering the impact mechanism of digital transformation affecting green technological innovation in manufacturing industries and providing practical insights for manufacturing enterprises to achieve sustainable development.

Specifically, this research is structured as follows. In Sections 2 and 3, the relevant literature on digital transformation, green technology innovation, and green dynamic capabilities are reviewed and four research hypotheses are presented. Section 4 describes the data collection, variable measurement, and econometric model. Sections 5 and 6 focus on the empirical results. Finally, the implications and limitations of this study are summarized in Sections 7 and 8.

2. Literature Review

This section provides a literature review of digital transformation, green technology innovation, and green dynamic capabilities, respectively.

2.1. Digital Transformation

Digital transformation is a change process in which organizations intend to achieve significant evolutionary refinement of their attributes through the combined use of technologies such as information, computing, communication, and connectivity [15], where the technology portfolio includes digital technologies such as big data, cloud computing, artificial intelligence, and blockchain. Organizations change their business models, production processes, and organizational structures during the transformation process of digital transformation [20].

In practice, digital transformation has a profound impact on society, industry, and enterprises at multiple levels, among which the effect on enterprise production activities based on resource-based view analysis is mainly manifested in two aspects: long-term competitive advantage and short-term organizational performance [15], whereby reducing costs, increasing revenue, improving efficiency, and encouraging innovation are the main ways of digital transformation to achieve enterprise development [21]. Regarding long-term competitive advantages: First, digital transformation can disrupt organizational production processes [22,23], such as the application of artificial intelligence algorithm technology based on big data analysis to the production line of manufacturing enterprises, which can realize automated algorithmic decision making and greatly improve production efficiency [23]. This disruptive application can effectively reduce the production cost of enterprises [24] and improve their total factor productivity [25]. Secondly, digital transformation can shorten the information transfer path between different management levels within a firm's organization [26], improve the efficiency of intra-organizational communication, and enhance a firm's dynamic ability to cope with changes in the external ambiguous and uncertain environment [27,28]. While digital transformation also helps firms to access competitive information and technological change directions in the market [29], keeping the organizational innovation team up to date and helping to improve the firm's innovation capabilities [30]; thus, firms can improve their organizational capabilities by implementing digital transformation, thus consolidating their long-term competitive advantage in the market. On the other hand, regarding short-term organizational performance: Firstly, digital transformation can increase the innovation performance by enhancing the innovation capability of the company [31]. Secondly, digital transformation can significantly reduce the production cost of the company and improve the organizational performance to achieve an increase in corporate profits [32]. In addition, digital transformation can help companies improve their reputation [33,34], expand robustly [35], and maintain a competitive advantage [36,37], among others.

Several studies have been conducted to analyze the enabling effects of digital transformation, such as innovation capability, dynamic capability, and competitive capability, but most of the studies on innovation capability are limited to the impact of a single digital technology on innovation capability or the innovation capability concept itself, and few studies have analyzed the impact of the change process of implementing digital transformation in enterprises on their green technology innovation. For example, Hanelt et al. [38] found that the application of information systems in enterprises can enhance the strength of green technology innovation, thus helping enterprises to transform into large-scale green sustainability. Ghobakhloo et al. [39] concluded that Industry 4.0 technologies can help enterprises to further improve the knowledge base of their organizational teams and the manufacturing capabilities of their production processes, enhancing sustainable innovation valuable organizational capabilities such as green absorptive capacity, green technological innovation capacity, etc., and in turn, through these organizational capabilities, achieve sustainable development. This study attempts to enrich the economic consequences of digital transformation by econometrically and empirically examining the role of the overall change of implementing digital transformation on corporate green technology innovation.

2.2. Green Technology Innovation

Green innovation is the reduction of environmental pollution through the application of new or improved practices, processes, technologies, systems, or products [40]. In addition, Albort-Morant et al. [13] define green technology innovation as "an innovation whose main objective is to mitigate or avoid environmental damage while protecting the environment and enabling firms to meet new consumer demands, create value and increase production". Studies and extensions of innovation theory are generally based on Schumpeter's innovation theory, which considers five types of innovation: product innovation, technological innovation, market innovation, resource allocation innovation, and organizational system innovation. When Schumpeter's innovation theory is applied to green innovation, it can also be divided into green product innovation, green technology innovation, etc. [41], where green technology innovation refers to any change or technological adjustment in the manufacturing process that helps to reduce the environmental pollution generated in the production process, such as the application of new technologies, innovative green patents, etc. [42]. This technological innovation can also improve productivity and organizational flexibility for companies [43].

Previous studies have mainly explored the influencing factors of green technology innovation from the perspective of external and internal factors [44], whereby the external factors mainly include two perspectives: system-driven and market-driven. From the system-driven perspective of external factors, strict environmental regulations, for example, can urge firms to engage in green technology innovation to avoid bearing pollution fines [3,4]. However, it has also been shown that stringent government environmental regulations will impose additional economic costs on manufacturing firms to undertake environmental responsibility, resulting in insufficient funds, which in turn serve as a disincentive for firms to engage in green technology innovation [45], so a reasonable intensity of government regulation becomes the key to whether it can promote green technology innovation among firms. In addition to mandatory government regulatory policies, incentive regulatory policies such as financial subsidies [5] and green finance [6] are also important factors to promote green technology innovation by enterprises; for example, government subsidies can help enterprises to share the additional economic costs and risks of technology fluctuations in green technology innovation [46]. From the market-driven perspective of external factors, stakeholder pressure from outside the organization can motivate firms to pursue green technology innovation [9], such as government support [7], customer demand [8], and knowledge sharing among industry chain partners [47], institutional investors [48], and public participation [49], as well as to seek to gain a long-term advantage in the competitive market may motivate firms to engage in green technology innovation. Regarding the study of internal influences on green technology innovation, the green orientation of the firm's management [10,11], organizational capacity [12,13], and organizational elements such as organizational governance structure [14] are important factors that influence green technology innovation.

Regarding the recent research on green technology innovation: First, most studies focus on the level of green innovation, and there is a lack of research refined into the five types of innovation under green innovation, such as green technology innovation. Secondly, most studies focus on the innovation performance, competitive advantage, and production optimization brought by green technology innovation capabilities for the corporate sector, while a relatively low percentage of research has been conducted on the impact factors [29]. Existing research also mainly focus on external factors [50], such as mandatory government regulations [51,52] and incentive regulations [5,53], external organizational stakeholder pressure [54,55], etc. The purpose of this study is to focus on the facilitation effect and the intrinsic influence mechanism of implementing digital transformation on corporate green technology innovation.

2.3. Green Dynamic Capability

Dynamic capability is the ability of a firm to perceive and access strategic opportunities and market needs in a complex external environment, and thereby coordinate, integrate, and reconfigure the organization's internal and external resource base to adapt to the new environment and gain a sustainable competitive advantage [56]. Based on dynamic capability theory, the green dynamic capability is the higher-order capability of a firm to respond to dynamic changes in the external market competition by developing, utilizing, and reconfiguring existing organizational resources and knowledge, and then renewing and developing a green organization to achieve sustainable development [57].

Green dynamic capability is one of the main factors that determine the development prospects of manufacturing enterprises. Green dynamic capability, as an advanced capability for enterprises to achieve green development, reflects the exploratory nature of enterprises [58], which enables them to utilize existing resources and knowledge to update and utilize green organizational capabilities to cope with the changing business environment [59]. With the behavior and response of enterprises in the process of seeking market opportunities, green dynamic capabilities are gradually becoming a lasting research topic. Firms can achieve green innovation in products and technologies by enhancing their green dynamic capabilities and seeking to achieve sustainable development under government environmental regulation and external stakeholder pressure.

3. Hypothesis Formulation

3.1. Digital Transformation and Green Technology Innovation

Firms use the changes and opportunities brought by digital technologies to accelerate the transformation of their production processes, business models, and production technologies [60], which continuously empower firms in this transformation process, such as innovation capabilities and dynamic capabilities. Research practice shows that encouraging innovation is one of the main ways in which digital transformation promotes the development of enterprises [21], and digital transformation positively affects the level of green technology innovation in enterprises [61]. The influencing factors of green technology innovation are mainly external and internal factors, and the promotion of digital transformation is mainly from the inside out, transforming the organization internally and thus empowering the enterprise, which makes the enterprise's green technology innovation ability improve.

First, digital transformation not only helps companies to obtain competitive information about the market and the direction of technological change [29], which keeps the organizational innovation team up to date, but also accelerates the speed and accuracy of information transfer within the organization and promotes information sharing within the company [26], which helps to improve the company's green innovation identification and thus promote green technology innovation in enterprises [18,19]. In addition, under the call of the digital economy and green sustainable development policies at the national level, digital transformation can help enterprises to strengthen communication with the government, reduce the cost of environmental information collection and analysis, and enable enterprises to quickly grasp the latest environmental policy changes and better grasp the direction of government environmental policies, which can help enterprises to obtain more government policy support [62], obtain government financial subsidies to alleviate the financing constraints of enterprises' green R&D activities, and encourage enterprises' green technology innovation [5,7].

Secondly, digital transformation can help enterprises break organizational boundaries and enhance connections with industry chain partner enterprises [63,64], which in turn improves the ability to obtain competitive market information and perceive the direction of technological change [29] and helps to obtain external green knowledge and improve green absorption capacity, which further improves the efficiency of external green knowledge adoption and promotes green technology innovation in enterprises [3]. For example, absorbing, processing, and transforming external green knowledge can enhance the green innovation awareness of corporate research teams and thus promote green technology innovation capabilities [65] and increase the level of ability to benefit from the implementation of environmental innovations [66]. In addition, establishing a network of digital information connections through digital transformation helps firms to stay connected with industry chain partners for collaboration and knowledge exchange [64], which can help firms to access new sources of external knowledge, technologies, and competencies and provide an external knowledge base for achieving green technology innovation [47].

Third, the process of change in implementing digital transformation in enterprises inevitably involves the introduction of digital technologies such as artificial intelligence, blockchain, and cloud computing, which are applied to help enterprises improve the quality and increase the quantity of technological innovation [63]. Ogbeibu et al. [67] found that the use of smart technologies, artificial intelligence, robotics, and algorithms (STARA) as well as other digital technologies can help management to enhance green creativity and thus promote the level of green technology innovation in enterprises. Tachia et al. [68] showed that disruptive technology blockchain can positively influence green technology innovation in enterprises through value distribution and is more effective in startups versus large enterprises. The study by Feng Yunting et al. [69] confirms that manufacturing enterprises can enhance their technological innovation capability from digital technology applications such as cloud computing and blockchain, and this can provide an innovative basis for green supply chain management. The process of digital transformation not only optimizes the organizational structure and business model of enterprises, but also introduces new digital technologies, improves the technological innovation awareness of technical teams, and provides the basis for further green technological innovation level of enterprises.

Based on the above analysis, the following hypothesis is proposed:

H1. *Digital transformation enhances green technology innovation of enterprises.*

3.2. Digital Transformation and Green Dynamic Capabilities

Digital transformation using digital technologies has had a profound impact on companies, not only changing the way they cope with uncertainty in the development process but also enhancing their ability to cope with this uncertainty [70]. The improvement of dynamic capabilities derives mainly from the influencing factors at both the organizational and the individual level [57], and digital transformation for green dynamic capabilities of enterprises is thus considered.

The main influencing factors at the organizational level are organizational culture, organizational structure, and information technology. First, digital transformation has an impact on the organizational culture of firms; for example, the implementation of digital transformation in firms positively affects international strategies, and firms with a higher degree of digitalization are more conducive to internationalization [71,72], while the diverse culture shaped by internationalization for companies can positively contribute to green dynamic capabilities [73,74]. Secondly, digital transformation can facilitate changes in organizational structure; for example, applying digital technology to implement digital transformation can shorten the information transfer path between different management levels within the organization [26], improve the efficiency of internal organizational communication [27], and enhance the green dynamic capability of the company to cope with external uncertain environmental changes [28]. Thirdly, digital transformation provides the basis for the application of digital technologies such as big data [17], artificial intelligence [23], etc., for organizations to develop green dynamic capabilities by deploying digital technologies to improve organizational processes [75,76].

The main influencing factors at the individual level are leadership style, employee creativity, managerial experience and skills, and managerial international perspective. First, in a competitive environment full of ambiguity, dynamism, and uncertainty, companies need transformational [59], entrepreneurial [77], and digital [78] types of leadership styles to lead organizations to enhance their dynamic capabilities to cope with risks, and the leadership styles of organizations undergoing digital transformation are more transformational and digital, which provides the basis for management capabilities to enhance the organization's green dynamic capabilities. Second, building a digital information network through digital transformation helps companies stay connected to the outside world [63], collaborate and exchange knowledge [64], and absorb, reconfigure, and apply external green sustainability knowledge [17], a process that not only increases managers' experience and skills but also enhances employees' creativity at the same time, which in turn leads to the enhancement of the organization's green dynamic capabilities. Third, the process of implementing international strategies in digital enterprises leads to the improvement of managers' international vision, which helps to build the green dynamic capability of the organization [58].

Based on the above analysis, the following hypothesis is proposed:

H2. *Digital transformation enhances the green dynamic capability of enterprises.*

3.3. Green Dynamic Capability and Green Technology Innovation

First, green dynamic capabilities empower organizations to identify green opportunities [56], which can improve the speed and accuracy of companies to obtain competitive market information and technology iteration direction, and quickly capture changes in customer needs through market research to accurately identify and determine opportunities for green product innovation and green process innovation [18,79]. Green dynamic capabilities provide information to support the first steps of green technology innovation and help to improve accuracy and success [9].

Second, green technology innovation relies on organizations to acquire green sustainability knowledge from outside and integrate it with internal knowledge and resources [3,13], and green dynamic capabilities can not only enhance the ability to acquire knowledge but also enhance the organization's absorptive capacity and improve the absorption and adoption of external knowledge [80].

Third, green dynamic capabilities can continuously strengthen team communication, collaborative efficiency, and internal adaptability within the organization [27], rationalize the coordination and utilization of resources, promote the repair, optimization, and renewal of its resource structure, and provide strong practical capabilities for green technology innovation [81].

Based on the above derivation, the following hypothesis is proposed:

H3. *Green dynamic capability enhances green technology innovation of enterprises.*

Based on the previous discussion and analysis in this chapter, we believe that dynamic capability should play an intermediary role in the process of digital transformation and upgrading enterprise green technology innovation. Therefore, we propose the following hypothesis:

H4. *Green dynamic capability plays an intermediary role in the process of digital transformation and upgrading enterprises' green technology innovation.*

The research model is shown in Figure 1.

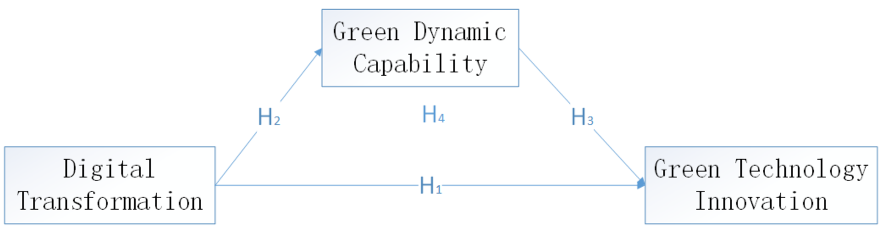

Figure 1. Research Model.

4. Variable Measurement and Measurement Model

Through theoretical analysis, digital transformation may either empower green technology innovation by directly enhancing the green dynamic capabilities of enterprises or by indirectly promoting green technology innovation by improving dynamic capabilities. In the following section, the study will empirically examine the relationship between digital transformation, green dynamic capabilities, and green technology innovation using econometric analysis.

4.1. Sample Selection and Data Sources

Since the rapid development of digital technologies such as the Internet, big data, artificial intelligence, and blockchain and the trend of implementing digital transformation of manufacturing enterprises in China mainly manifested after 2007, this study takes A-share manufacturing listed companies from 2007 to 2020 as the initial research sample and screens the samples according to the following principles: (i) excluding ST, PT, and insolvent samples; (ii) excluding samples with missing relevant variables. Finally, 20,283 annual observations of 2049 listed companies were obtained. The financial data of companies are mainly obtained from the database of Guotaian (CSMAR), and the regional data are mainly obtained from the China City Statistical Yearbook in previous years.

4.2. Variable Measures

1. Core explanatory variables: digital transformation

Based on the existing research, we build a digital lexicon specifically for manufacturing enterprises by combining the national policy text supporting the digital transformation of manufacturing enterprises and existing digital transformation indicators and establish a more systematic proxy variable representing the degree of digitalization of listed manufacturing enterprises based on this lexicon using text analysis methods [32]. The specific steps are as follows.

The first step was to build a dictionary of digital terms for manufacturing enterprises.

Because of the lack of digital transformation terminology dictionaries that can be directly used for textual analysis of annual reports of listed manufacturing enterprises, this study constructed its own terminology dictionary related to the digital transformation of listed manufacturing enterprises based on the dictionary-building method. In order to ensure that the digital transformation keywords in the terminology dictionary have certain accuracy, authority, and comprehensiveness, and focus on the specific processes and empowering effects that can describe the implementation of digital transformation in manufacturing industry enterprises to a certain extent, a dictionary of digital terms for manufacturing industry enterprises was constructed based on the semantic system of national policies. Six keywords such as digital economy, digital transformation, artificial intelligence, blockchain, cloud computing, and big data were used as clues to obtain the digital terminology by searching the policy release section of the official website of the Central People's Government (http://www.gov.cn, accessed on 3 April 2022) and the policy release section of the official website of the Ministry of Industry and Information Technology (www.miit.gov.cn, accessed on 3 April 2022), and manually screening them to obtain the information. The 28 important national-level policy documents related to the digital transformation of manufacturing industry enterprises as of December 2021 were used as the source for extracting specific keywords for the digital transformation of manufacturing industry enterprises [82].

Next, the core contents of the above 28 policy documents were summarized into a txt file, and the text contents of the policy documents were segmented in multiple rounds by using the jieba splitting database and selecting the filtered discontinued words, policy terms, and other irrelevant words as the segmentation basis. The contents were trimmed down to obtain about 1500 unique words, of which 57 terms or phrases related to the digitalization of manufacturing enterprises were obtained.

Finally, the 57 terms obtained from the above national policy documents were combined with the manufacturing-industry-related terms from the existing digital transformation indicators to obtain the final digital transformation dictionary for Chinese manufacturing listed companies in this study, with a total of 85 terms.

In the second step, a textual analysis of the MD&A section of the annual report was performed using the dictionary.

Using a machine learning crawler method, we downloaded the annual reports of A-share manufacturing companies from 2007 to 2020 from Juchao Information Website (www.cninfo.com.cn, accessed on 20 April 2022) and extracted the "Management's Discussion and Analysis (MD&A)" section (due to the adjustment of the annual report disclosure format, the "Board of Directors' Report" section was extracted before 2014). Using the 85 terms in the dictionary of digital terms for manufacturing companies constructed in the first step, the text of the MD&A section of each listed manufacturing company's annual report was word-sorted based on machine learning, and the frequency of the 85 terms related to the digital transformation of manufacturing companies in the dictionary was queried and counted from the word-sorting results, and the total number of words in the MD&A section was also counted. There are two explanations for the above process, as follows: 1. The reason for choosing the MD&A part of the annual reports of listed companies as the text analysis object is to consider that the content of the MD&A part is most likely to describe the digital transformation of enterprises. The implementation of digital transformation in enterprises is not simply the application of digital technology, but the integration of digital technology into the process of enterprise operation by using the data generated in the process of production, operation, and management of enterprises as the driving factor. It is essentially a strategic action to improve the enterprise's response to undirected technological advances and competitive market risk fluctuations by introducing digital technologies [83]. As can be seen, digital transformation is closely related to the development strategy, business operations, risk response, and other important features of the enterprise. Therefore, to ensure as much as possible the degree of fit between the construction of digital indicators and the actual situation of the enterprise's digital transformation, the selection of the textual analysis object should fully consider the disclosure vehicle of information on the above-mentioned features. The MD&A section of the annual report usually discloses and analyzes the company's development strategy, business operation, risk response, organizational change, etc. [32], so the MD&A section is used as the text analysis object to ensure that the collected corporate digital keywords match the real digital transformation situation of the company, so as to ensure the reliability of the indicator construction. 2. The following trade-offs are made for the selected objects: (1) excluding non-regularly traded listed companies (including ST, ST*, and PT); (2) excluding companies that have published their annual reports for less than four years; and (3) excluding companies with more years of missing data of important variables. Finally, 2049 listed manufacturing companies were obtained as the research subjects, with a total of 20,283 sets of observation data.

The third step was to build digital transformation variables.

The number of occurrences of words in the digital transformation terminology dictionary in the MD&A section of the annual reports published by the sample companies during the sample period was extracted using text analysis methods, and this value was used as a preliminary textual basis to quantify the degree of digital transformation of the companies. Since the number of words in the MD&A section of the annual report varies, the value was processed as follows: the total number of occurrences of digital-transformation-related words in the MD&A section of the annual report was divided by the total number of words in the MD&A section of the annual report, and this standardized ratio was used to measure the degree of digital transformation (Digital) of the enterprise. For counting convenience, the obtained digital transformation variables were multiplied by 1000, and the higher the value changed, the higher the degree of digital transformation of the company.

2. Explanatory variable: green technology innovation

Referring to previous research [84], the number of green patent applications was used as a proxy variable for the degree of green technological innovation of the enterprise in that year. In detail, since the external-type patents were not considered as green patents and the degree of technological innovation of utility model patents was not high, this study innovatively used the number of green invention patent applications as the main measurement variable, while the number of green utility model patent applications was used as a comparative indicator to measure green technological innovation. To eliminate the problem of the right-skewed distribution of green patent application data, the number of green patent applications was added by 1 and then taken as the natural logarithm.

3. Mediating variable: green dynamic capacity

Green dynamic capability is a multidimensional aggregation structure [85], and the measurement of green dynamic capability is mainly based on three sub-capabilities: perception capability, utilization capability, and transformation capability [40]. Based on previous research [86], the three sub-capabilities are measured using three enterprise data: First is the number of effective patents in the year, which reflects the enterprise's ability to perceive environmental changes and grasp innovation opportunities. Second is the number of employees with postgraduate education or above, which can reflect the learning ability and comprehensive quality of employees to a greater extent and can show the ability of enterprises to utilize digital technology. Third is the ratio of current assets to revenue, which represents faster business turnover and stronger liquidity of enterprises and reflects the transformation ability of enterprises. The above three indicators are analyzed by PCA (principal component analysis) to obtain a comprehensive score of GDC to measure the green dynamic capability.

4. Control variables

To control for other indicators of economic characteristics that affect corporate green innovation, a series of control variables were introduced with reference to existing literature practices [84,87,88]. These include: fixed assets ratio (Ppe), dual chairman and CEO positions (Dual), corporate operating cash ratio (Cash), gearing ratio (Debt), return on assets (Roa), employee size (Employee), capital expenditure ratio (Capital), stock book-to-market ratio (BM), and independent director ratio (Ind_ dir).

Table 1 presents the statistical descriptions of all variables.

Table 1. Descriptive statistics.

Variable	Name	N	Mean	Sd	Min	Max
GTI	Green Technology Innovation	20,283	0.910	1.190	0	7.390
Digital	Digital Transformation	20,283	0.390	0.820	0	12.37
GDC	Green Dynamic Capabilities	20,283	2.010	1	−0.345	36.42
Ppe	Percentage of Fixed Assets	20,283	0.002	0.001	0	0.009
Dual	Chairman of the Board and CEO of the Company	20,283	0.304	0.460	0	1
Cash	Corporate Operating Cash Ratio	20,283	0.010	0.025	−0.043	0.751
Debt	Gearing Ratio	20,283	0.004	0.009	0	0.970
Roa	Return on Assets	20,283	0.0005	0.0019	−0.0671	0.2079
Employee	Employee Size	20,283	7.690	1.189	1.386	12.34
Capital	Capital Expenditure Ratio	20,283	0.028	0.040	0	1.936
BM	Stock Book-to-Market Ratio	20,283	0.580	0.250	0.010	1.460
Ind_dir	Percentage of Independent Directors	20,283	0.373	0.972	0.588	0.833

4.3. Empirical Model Construction

Drawing on previous research and the suggestions of academic studies on mediating effects, the following econometric model was constructed.

$$GTI_{it} = \alpha_1 + \beta_1 Digital_{it} + Controls_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (1)$$

$$GDC_{it} = \alpha_2 + \beta_2 Digital_{it} + Controls_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (2)$$

$$GTI_{it} = \alpha_3 + \beta_3 GDC_{it} + Controls_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (3)$$

$$GTI_{it} = \alpha_4 + \beta_4 Digital_{it} + \beta_5 GDC_{it} + Controls_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (4)$$

where the explanatory variable GTI_{it} denotes the level of green technology innovation of firm i in year t, and the core explanatory variable $Digital_{it}$ is the degree of digital transformation of firm i in year t. $Controls_{it}$ are a set of control variables, μ_i is the individual effect of each firm that does not vary over time, and ν_t is the time effect. Model (1) is used to test hypothesis H_1, and if the coefficient α_1 of $Digital_{it}$ is significantly positive, it indicates that digitization can promote the level of green technology innovation of enterprises, which is consistent with hypothesis 1; model (2) is used to test hypothesis H_2, if the coefficient α_2 of $Digital_{it}$ is significantly positive, it proves that digitization can improve the green dynamic capability of enterprises; model (3) is used to test hypothesis H_3, and if the coefficient α_3 of GDC_{it} is significantly positive, it shows that green dynamic capabilities can enhance the level of green technology innovation of enterprises; models (1) and (2) in conjunction with (4) can test hypothesis H_4, which proves that green dynamic capabilities play a mediating role in digital transformation positively affecting green technology innovation.

5. Results

5.1. Baseline Regression

Table 2 shows the results of the baseline regressions of this study. In this case, the regression in the first column only controls for year-fixed effects and individual fixed effects without adding control variables; the regression in the second column adds the rest of the required control variables. The results show that the “Digital” regression coefficients of both regressions are significantly positive (β = 0.0755, $p < 0.001$; β = 0.0585, $p < 0.001$), indicating that the higher the degree of digital transformation of a company, the stronger its green technology innovation capability will be. Taking the regression results in the second column as an example, each 1 percentage point increase in the level of digital transformation of enterprises will lead to a simultaneous increase in the level of green technology innovation by 0.0585, i.e., an increase of about 6.4% (0.0585/0.91 × 100%) compared to the mean value of 0.91 in the level of green technology innovation of enterprises during the sample period. The baseline regression practice proves hypothesis H_1, that digital transformation has a positive impact on enterprises’ green technology innovation, and that the implementation of digital transformation by enterprises will promote the improvement of green technology innovation level, which will reduce cost and increase the efficiency and improve the capability of enterprises.

Table 2. Baseline regression.

	GTI		**GTI**
Digital	0.0755 *** −5.37	Digital	0.0585 *** −4.45
		Ppe	−22.92 **
		Dual	−0.0011
		Cash	0.7001 **
		Debt	3.318 ***
Control variables	No	Roa	4.601 **
Year FE	Yes	Employee	0.3079 ***
Individual FE	Yes	Capital	0.016
		BM	0.2151 ***
		Ind_dir	−0.0126
		Year FE	Yes
		Individual FE	Yes
_cons	0.0800 ** −2.62	_cons	−2.218 *** −11.91
N	20283	N	20283
adj. R-sq	0.2375	adj. R-sq	0.2776

Note: t statistics in parentheses. ** $p < 0.01$,*** $p < 0.001$.

5.2. Mediation Effect Test

In this study, we refer to the recursive equation to test the mediating effect. First, the mechanism of "digital transformation-green dynamic capability-enterprise green technology innovation" is identified and tested. The results shown in the first column of Table 3 are the effect of digital transformation on green technology innovation with the inclusion of control variables and fixed effects, which have been explained above and will not be reiterated here. The results in the second column of Table 3 are the regression of Equation (2), and the results show that digital transformation helps to improve the green dynamic capability of enterprises ($\beta = 0.0971$, $p < 0.01$), that is, hypothesis H_2 is verified by the econometric regression. The results in the third column of Table 3 are the regression of Equation (3). The fourth column presents the regression of Equation (4), which is the regression of enterprise green technology innovation capability on digital transformation and green dynamic capability. The regression coefficient of digital transformation is 0.0482 and that of green dynamic capability is 0.1060, which both pass the 1% statistical significance test. Compared with the regression result in the first column, the regression coefficient value of digital transformation decreases but is still significantly positive in the fourth column after adding green dynamic capability, and the joint (1), (2), and (4) model can initially indicate the existence of the mediating effect of green dynamic capability, i.e., hypothesis H_4 is verified through empirical testing.

Table 3. Mediation effect test.

	GTI	GDC	GTI	GTI
Digital	0.0585 *** −4.45	0.0971 ** −2.9		0.0482 *** −3.77
GDC			0.1105 *** −4.6	0.1060 *** −4.5
Ppe	−22.92 **	−4.13	−24.29 **	−22.49 **
Dual	−0.0011	0.1482	−0.0043	−0.0027
Cash	0.7001 **	0.4829 **	0.6114 **	0.6489 **
Debt	3.318 ***	1.128 **	3.214 ***	3.199 ***
Roa	4.601 **	−11.03 **	5.783 **	5.771 **
Employee	0.3079 ***	0.1367 ***	0.2963 ***	0.2934 ***
Capital	0.016	0.0911	0.0095	0.0064
BM	0.2151 ***	0.0899 **	0.2036 ***	0.2056 ***
Ind_dir	−0.0126	−0.0784	−0.0044	−0.0044
Year FE	Yes	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes	Yes
_cons	−2.218 *** −11.91	−1.286 *** −9.43	−2.087 *** −11.20	−2.082 *** −11.21
N	20283	20283	20283	20283
adj. R-sq	0.2776	0.0726	0.2821	0.2832
Sobel test	Z = 8.765 ***			
Bootstrap	[0.024–0.040]			

Note: t statistics in parentheses. ** $p < 0.01$, *** $p < 0.001$

To ensure the robustness of the intermediary mechanism, this study uses two methods, Sobel and Bootstrap, to test the robustness of the above intermediary path, and the results show that the Z value of the Sobel test is 8.756 and the confidence interval of Bootstrap test does not contain 0. The robustness of the intermediary effect is verified to some extent. Given the above empirical analysis, this study finds that the digital transformation of enterprises can enhance the level of green innovation technology by improving the green dynamic capability of enterprises.

5.3. Endogeneity Issues

The basic conclusions above may be challenged by endogenous issues. On the one hand, firms implementing digital transformation will improve green dynamic capabilities and enhance green technology innovation; on the other hand, firms with higher levels of green technology innovation may also have a stronger need to promote high levels of digitalization to facilitate innovation capabilities, ability to cope with complex ambiguous and uncertain environments, and rapid response capabilities. To mitigate as much as possible the potential endogenous influence of this reverse causality on the findings, this study uses an instrumental variable approach to test it.

In this study, two types of instrumental variables are adopted to test each of these variables. The first is based on the approach of previous research—the Internet penetration rate in the previous periods of the sample period is used as an instrumental variable, and the regional Internet penetration rate reflects to a certain extent the penetration of digital technology in local enterprises and is not directly related to the green technology innovation of enterprises. Secondly, we select an instrumental variable—the level of digital transformation with a one-period lag—as an instrumental variable by drawing on idea of previous research [89].

In Table 4, the first and second columns report the test results for the two instrumental variables, respectively, showing that the regression coefficient of the independent variable "Digital" remains significantly positive, indicating that the findings of the baseline regression of this study are robust and reliable with some robustness.

Table 4. Instrumental variable method.

	GTI	GTI
Digital	0.4092 ** −2.97	0.1996 *** −5.93
Ppe	−37.74 ***	−21.23
Dual	−0.0324	0.0025
Cash	−0.6945	0.9655 **
Debt	0.3522	3.145 ***
Roa	−0.8418	5.191 ***
Employee	0.0697 ***	0.2937 ***
Capital	0.0822	0.0011
BM	−0.0252	0.2140 ***
Ind_dir	−0.0083	−0.0047
Year FE	Yes	Yes
Individual FE	Yes	Yes
N	20283	20283
Kleibergen-Paap rk LM statistic	8.83	359.925
Cragg-Donald Wald F statistic	25.73 [16.38]	3379.614 [16.38]

Note: t statistics in parentheses. ** $p < 0.01$, *** $p < 0.001$.

The above instrumental variables were tested as follows: Kleibergen–Paap rk LM statistic was significant at 1% level, and the original hypothesis of under-identification of instrumental variables was rejected; Cragg–Donald Wald F statistic was greater than the critical value of Stock–Yogo weak instrumental variable identification F test at 10% significance level, and the original hypothesis of weak instrumental variables was rejected. In summary, the instrumental variables selected for this study are reasonably reliable.

5.4. Robustness Tests

5.4.1. Replacement Estimation Model

Since the original data of "GTI" takes the value of [0, + ∞), it is still typical truncated data after adding 1 to the original data to take the logarithm, so the Tobit model, which has a better fit to the truncated data, is used to re-estimate. The test results are shown in the first column of Table 5, and the regression coefficient of "Digital" on "GTI" is 0.2709 ($p < 0.001$), which is consistent with the baseline regression results.

Table 5. Robustness tests.

	GTI	**GTI_0**
Digital	0.2709 *** −16.69	0.0453 *** −3.64
Ppe	−209.756 ***	−9.965
Dual	−0.0237	0.1207
Cash	−2.606 ***	0.8079 **
Debt	5.447 **	2.6855 ***
Roa	−49.04 **	4.301 **
Employee	0.6927 ***	0.2250 ***
Capital	1.856 ***	0.1219
BM	0.5857 ***	0.1398 ***
Ind_dir	−0.3904 **	−0.049
Year FE	Yes	Yes
Individual FE	Yes	Yes
_cons	−6.440 *** −43.35	−1.686 ** −10.64
N	20283	20283
adj. R-sq	0.0986	0.1955

Note: t statistics in parentheses. ** $p < 0.01$, *** $p < 0.001$.

5.4.2. Change the Measurement of Green Technology Innovation in Enterprises

In the benchmark regression, since the external type patents are not considered as green patents and the degree of technological innovation of utility model patents is not high, this study innovatively takes the number of green invention patent applications as the main measurement variable, and the number of green utility model patent applications as an alternative indicator to measure green technological innovation in the robustness test. The test results are shown in the second column of Table 5. The regression coefficient of "Digital" on "GTI_0" is 0.0453 ($p < 0.001$), which is consistent with the baseline regression results and passes the test.

5.4.3. Explanations That Exclude Strategic Corporate Behavior

Although the digital transformation level index constructed by text analysis of listed enterprises' annual reports through machine learning methods in this study can reflect the implementation of digital transformation of enterprises in the current year to a certain extent, there may be strategic speculation or hotspots in the current year when enterprises disclose information related to enterprises in their annual reports. For example, if the capital market is enthusiastic about the digital transformation concept, the management of the company may mention too much digital-related content in the annual report to enhance the company's stock price. Previous studies show that listed companies may engage in hot speculation, exaggerated information disclosure, or may misrepresent corporate achievements in their annual report disclosure [90]. To exclude such strategic corporate speculation, this study conducted the following robustness tests: (1) This study excluded the samples that did not mention digital-transformation-related terms in their annual reports during the sample period, and we re-tested the regression results in the first column of Table 6. (2) We excluded the dataset of the sample whose digital-transformation-related content in the annual reports may have been exaggerated. Specifically, the sample with the highest 10% of the independent variable digital transformation is excluded and retested, and the regression results are presented in the second column of Table 6. (3) The sample of companies that have been punished by the SEC or stock exchange for non-compliant information disclosure and stock price speculation from 2007 to 2020 is removed, and the regression results are presented in the third column of Table 6.

Table 6. Regression results of the test for exclusion of strategic corporate behavior.

	GTI	GTI	GTI
Digital	0.0282 **	0.1033 ***	0.0692 ***
	−2.19	−3.7	−3.35
Ppe	−23.22	−23.57 **	−0.2813
Dual	0.0041	−20	0.0075
Cash	1.017 **	0.6484 **	−0.0067
Debt	1.227	3.316 ***	0.0088 ***
Roa	−3.958	4.606 **	−0.0102
Employee	0.4053 ***	0.3087 ***	0.00001 **
Capital	0.4348 **	0.131	0.00005
BM	0.1412 **	0.2144 ***	0.2316 **
Ind_dir	−0.0236	−0.0169	−0.0021
Year FE	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes
_cons	−3.080 ***	−2.154 **	−0.009
	−11.83	−11.91	−0.09
N	12015	18255	8247
adj. R-sq	0.262	0.2657	0.272

Note: t statistics in parentheses. ** $p < 0.01$, *** $p < 0.001$.

From the regression results, it can be seen that the coefficients of "Digital" in the three robustness tests excluding strategic corporate behavior are significantly positive, which is consistent with the results of the benchmark regression, indicating that digital transformation significantly promotes corporate green technology innovation, and to some extent excludes the influence of possible strategic disclosure behavior of companies in their annual report disclosure.

5.4.4. Lagged Regression

In this study, the number of green patent applications in the current year is used as a proxy variable to measure green technology innovation. Considering that patent output has a certain lag—one is that it takes some time from patent application to final grant, and the other is that enterprises may delay the publication of patent information for the purpose of protecting patented technology—therefore, the two green technology innovation proxies used in the previous paper are regressed with a one-period lag for robustness testing, and the results are shown in Table 7's first and second columns, respectively. The regression coefficients are significantly positive, which are consistent with the baseline regression results.

Table 7. Lagged one-period regression.

	L.GTI	**L.GTI$_0$**
Digital	0.0786 **	0.0774 **
	−3.32	−3.86
Ppe	−13.08 *	−0.4999
Dual	−0.0167	0.0029
Cash	0.3633	0.5700 *
Debt	3.008 ***	2.261 ***
Roa	4.47	1.731
Employee	0.2630 ***	0.1887 ***
Capital	−0.3918**	−0.136
BM	0.2115 ***	0.1359 ***
Ind_dir	−0.2387	0.0526
Year FE	Yes	Yes
Individual FE	Yes	Yes
_cons	−0.216 **	−0.258 ***
	−2.92	−4.14
N	20283	20283
adj. R-sq	0.2855	0.199

Note: t statistics in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

6. Discussion

To further verify the reliability of the results of the previous empirical study, a robustness test analysis of the study is described below.

6.1. Heterogeneity Analysis

This study focuses on the impact of digital transformation on green technology innovation in Chinese manufacturing listed enterprises. From the national research data, it can be seen that Chinese manufacturing enterprises are characterized by a complex nature, wide geographical distribution, and large differences in enterprise scale, so the following heterogeneity analysis is conducted based on enterprise ownership, enterprise location, and enterprise scale.

6.1.1. Business Ownership

The results are summarized in Table 8. The coefficient of non-state-owned enterprises is 0.137, while the coefficient of state-owned enterprises is 0.228. It can be seen that the digital transformation of state-owned enterprises has a greater positive effect on green technology innovation (0.228 > 0.137). Compared with non-SOEs, SOEs have more obvious advantages in terms of resources, talents, and policy support, and because of their special property rights, the promulgation of national policies such as digital transformation and green development will often be better implemented in SOEs. Once the transformation is implemented, the practical effect will be better than that of non-SOEs. In addition, both digital transformation and green technology innovation are risky, have long payback periods, and require large amounts of resources, so SOEs' advantages in resource reserves will come into play in digital transformation and green technology innovation.

Table 8. Regression results of enterprise ownership grouping.

	Non-State-Owned Enterprises	State-Owned Enterprise
	GTI	GTI
Digital	0.137 *** −7.29	0.228 *** −5.58
Control variables Year FE Individual FE	Yes Yes Yes	Yes Yes Yes
_cons	0.456 *** −6.02	0.680 *** −4.77
N	13556	6727

Note: t statistics in parentheses. *** $p < 0.001$.

6.1.2. The Area Where the Enterprise Is Located

The results are shown in Table 9. The standardized regression coefficients of "Digital" are 0.155, 0.203, and 0.285, respectively, and the regression coefficients show a gradual increase from east to west. From the analysis of the results, it is clear that the positive effect of digital transformation on green technology innovation is more obvious (0.285 > 0.203 > 0.155) as the geographical location tends to be closer to the western inland. The industrial distribution of China's manufacturing industry can be roughly described as comprised of the large proportion of traditional manufacturing industries in the central and western regions, the significant effect of industrial upgrading to technology-intensive manufacturing in the eastern coastal regions, and the significantly higher degree of industrial structure optimization in the eastern regions than in the central and western regions. This industrial layout characteristic leads to a greater demand for green technology innovation and innovation space for enterprises in the central and western regions, and greater local policy support, so that digital transformation with the enterprises' own development motivation and external support can better promote their achievement of green technology innovation effectiveness.

Table 9. Regression results for the group of enterprise location.

	East	Middle	West
	GTI	GTI	GTI
Digital	0.155 *** −7.78	0.203 ** −6.08	0.285 *** −6.88
Control variables Year FE Individual FE	Yes Yes Yes	Yes Yes Yes	Yes Yes Yes
_cons	0.585 *** −6.73	0.434 *** −2.88	0.261 * −1.88
N adj. R-sq	13799 0.286	3580 0.131	2904 0.274

Note: t statistics in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

6.1.3. Enterprise Size

In addition, the enterprises were further classified into four sizes of enterprises: micro, small, medium, and large according to the national standards. Since there are no micro enterprises in the manufacturing listed enterprises under the current national standards, only three sizes of small, medium, and large are included in the final classification of the research subjects. The regression results are shown in Table 10, and the standardized regression coefficients of "Digital" for small, medium, and large enterprises are 0.050, 0.536, and 0.155, respectively, which pass the group coefficient difference significance test. From the analysis of the regression results, it can be seen that the implementation of digital transformation in medium-sized enterprises has a more significant positive effect on their own green technology innovation, and the effect is much greater than that of small and large enterprises, so it is obvious that there is a scale effect and an inverted U-shape in the implementation of digital transformation in enterprises. The possible reasons are that medium-sized enterprises have more capital than small enterprises to support the cost increase brought by digital transformation and green technology innovation, and their talent pool, professional division of labor, and enterprise management are more complete, and that medium-sized enterprises are more flexible than large enterprises, they can react and respond quickly when facing the turbulence brought by digital transformation, and they are also more willing to reform and innovate.

Table 10. Regression results of firm size grouping.

	Small	**Medium**	**Large**
	GTI	**GTI**	**GTI**
Digital	0.050 ** −3.31	0.536 ** −2.69	0.155 ** −2.69
Control variables	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes
_cons	−0.190 ** −2.48	0.024 −0.22	2.040 * −1.84
N	9968	10021	285
adj. R-sq	0.137	0.301	0.547

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

6.2. Economic Consequences: The Impact of Digital Transformation on Business Costs

The process of digital transformation inevitably brings about short-term cost increases, but at the same time, digital transformation empowers enterprises to enhance their own green technology innovation and other series of capabilities that can also alleviate the cost pressure in this process to a certain extent. Table 11 shows the economic consequences of digital transformation for green technology innovation, showing the change of cost in the process of digital transformation. As can be seen from the table, the implementation of digital transformation in manufacturing industry enterprises inevitably raises production and operation costs, but at the same time can promote enterprises' green technology innovation capabilities and improve their green performance to reduce certain production costs, which in turn plays a disguised role in reducing the incremental costs incurred by enterprises for the implementation of digital transformation.

Table 11. Regression results of the economic consequence test.

	Costs	**GTI**	**Costs**
Digital	0.0357 ** −3.31	0.0655 *** −4.99	0.0282 ** −2.73
GTI			0.113 *** −8.96
Control variables	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes
_cons	20.10 *** −297.59	−0.126 * −2.04	−0.0593 −0.96
N	20283	20283	20283
adj. R-sq	0.262	0.262	0.267
Sobel test		Z = 17.71 ***	
Bootstrap		[0.038–0.050].	

Note: t statistics in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

7. Conclusions

7.1. Theoretical Contribution

Digital transformation is an important means for enterprises to achieve high-quality development. In the context of carbon peaking and carbon neutrality, what is the role of digital transformation in the green technology innovation of enterprises? In this context, this study crawls through the keywords of "digital transformation" in the annual reports of listed companies, constructs digital transformation indicators at the enterprise level, and studies the impact of digital transformation on enterprise green technology innovation. The findings are as follows: (1) Digital transformation has a significant positive impact on corporate green technology innovation, and this finding still holds after multiple robustness tests. (2) Green dynamic capabilities play a mediating role in the process of digital transformation of enterprises to promote green technology innovation and promote digitalization to function more effectively. (3) Heterogeneity analysis shows that digital transformation by state-owned, mid-western, and medium-sized firms is more significantly effective in promoting green technology innovation than non-state-owned, eastern, and small and large firms. (4) The economic consequence test shows that digital transformation can reduce the incremental costs incurred by enterprises in the process of digital transformation by promoting green technology innovation in enterprises.

This study enriches the study of the enabling effects of digital transformation and extends the antecedents of green technology innovation, in addition to examining the mediating effects of green dynamic capabilities in the process of digital transformation to enhance green technology innovation.

7.2. Practical Implication

According to the above findings, the following four insights can be obtained.

First, manufacturing enterprises should deeply implement digitalization strategies to enhance the dynamic ability to cope with complex, ambiguous, and uncertain environments, and thus empower their green technology innovation capabilities. The analysis of economic consequences shows that digital transformation is in the initial stage of increasing enterprise cost, which causes larger resource investment and squeezes enterprise profit, but enterprises can enhance enterprise capability such as green technology innovation through digital empowerment to relieve cost pressure.

Second, digitalization and green innovation are both risky and resource-dependent and require continuous strengthening of resource investment. However, it is also necessary to evaluate the innovation output effect of resource input in a timely manner and grasp the appropriate scale of resource input, which needs to match the business condition and capacity of enterprises.

Third, the heterogeneity analysis shows that the nature of ownership, geographical location, and enterprise size all have heterogeneous effects on the effectiveness of enterprise green technology innovation, which reveals that the management of non-state enterprises should fully analyze their own reform risk resistance, improve the efficiency of resource utilization, and reduce the possible adverse effects in the process of digital transformation. Enterprises in central and western China, i.e., with lower industrial level, should increase their attention to digital transformation, and green medium-sized enterprises should dare to break through the status quo, make full and reasonable use of their scale advantages to carry out reforms, properly implement digital transformation, and promote green technology innovation. Small enterprises should first focus on resource accumulation to improve their survivability and seek digital reform after gaining a certain ability to resist risks, while large enterprises should maintain their leading position in the industry and at the same time carry out appropriate optimization and reform of the production chain to improve their ability to cope with the complex, ambiguous, and uncertain environment.

Fourth, under the condition of controllable cost investment, using digitalization to improve the quality of operation, reduce costs, and increase efficiency is a necessary condition for enterprises to survive longer in the era of stock, and the reasonable use of digitalization to empower enterprises can reduce the burden of increased costs in the process of implementing digitalization and achieve controllable cost investment.

8. Limitation and Future Direction

Currently, measurement of the digital transformation of a large sample of enterprises is still being explored. We have provided a text analysis method that effectively measures the digital transformation of a large number of enterprises, but this method has a limitation in that it does not take into account the background of the text.

Future research can expand on this method and find ways to improve it.

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