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The impact of digital transformation on green technology innovation in manufacturing enterprises: Empirical evidence based on text analysis

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Abstract: The research investigates how digital evolution affects innovation in eco-friendly technology within A-share listed manufacturing companies between 2010 and 2022. Employing textual examination to derive terms associated with "digital transformation" from yearly summaries, the study evaluates the extent of digitization in businesses. Findings indicate a substantial enhancement in green technology innovation due to digital transformation, with financial and economic development levels acting as mediators. Heterogeneity analysis reveals that the impact varies by ownership structure, financial market environment, and executive shareholding. This research proposes strategies to boost innovation in green technology via digital transformation, aiding in the sustainable growth of China's manufacturing industry.

Keywords: *Corporate sustainable development, Digital transformation, Green technology innovation, Manufacturing.*

1. Introduction

In the midst of worldwide efforts towards sustainable growth, balancing economic expansion with environmental conservation has emerged as a vital concern for nations globally [1]. As the core driver of economic growth, the manufacturing industry is also a major source of resource consumption and environmental pollution. Therefore, Advancing innovation in green technology within manufacturing companies to cut down on pollution emissions and improve the efficiency of resource use is a crucial route to attaining eco-friendly development [2]. Lately, due to the swift progress in digital tech, digital transformation has slowly become a crucial strategy for propelling the eco-friendly evolution of the manufacturing industry. Digital transformation not only alters traditional manufacturing production models and management approaches but also provides vital technological support for green technology innovation, enabling enterprises to optimize production processes and minimize resource wastage, thereby promoting environmentally-friendly development [3].

Utilizing digital innovations, including the Internet of Things (IoT), cloud computing, and extensive data. Plus the realm of artificial intelligence, allows enterprises to optimize resource usage through real-time data analysis and accurately monitor the environmental impacts in their production processes, thereby cutting down on energy use and emissions of pollutants. Consequently, analyzing the distinct effects of digital change on the innovative green technology skills of manufacturing companies is crucial both theoretically and practically. The color value. The research presents fresh viewpoints on the role of digital technologies in fostering eco-friendly innovation and also supplies actionable knowledge for decision-makers to advance the green evolution of the manufacturing industry [4].

Studies exploring the link between digital evolution and corporate innovation have achieved significant advancements. Research indicates that digital technologies play a crucial role in fostering

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technological advancements and enhancing production efficiency. Along with enhancing the supply chain [5]. Within the realm of green technology innovation, certain academics have noted that digital advancements subtly boost a company's capacity for green innovation through the efficient distribution of resources, advocating for energy preservation, and diminishing environmental pollution. Formula [6]. Nonetheless, the majority of current research concentrates on how digital transformation affects general innovation abilities [7]. There is a scarcity of empirical studies regarding its distinct function in advancing green technology, especially concerning the routes it uses to promote green innovation.

Initially, quantitative studies are scarce regarding the role of digital transformation in fostering innovation in green technology, with most studies remaining at the theoretical or case analysis level, and lacking empirical support from large-scale enterprise data [8]. Second, Current studies infrequently investigate how digital transformation variably affects diverse business sectors. Particularly, in firms with varying ownership structures, financial market environments, and executive stock ownership ratios, the green innovation effects of digital transformation may exhibit significant heterogeneity. Moreover, Existing literature offers scant comprehensive examination of how financial and economic growth mediate the link between digital transformation and the innovation of green technology. Such elements could have an indirect impact corporate eco-friendly innovation by offering support for resources and fostering advantageous market scenarios. Consequently, current studies still have a significant void in uncovering the distinct processes and varied impacts of digital transformation on the innovation of green technology.

In an effort to bridge these voids, this study undertakes a practical examination of the link between digital evolution and the advancement of green technology, utilizing micro panel information from Chinese manufacturing companies. Through the creation of measurement metrics This research delves deeply into the role of digital transformation in fostering green tech innovation via financial and economic growth. Financial development optimizes financing channels and capital allocation, providing necessary funding support for technological innovation, whereas economic growth provides a conducive market setting that encourages the spread and utilization of eco-friendly technologies.

Furthermore, this paper conducts a heterogeneity analysis to examine the moderating effects of ownership structure, financial market environment, and the role of executive stock ownership in the link between digital transformation and the innovation of green technology. Variations in the composition of ownership could result in differing levels of motivation and the distribution of resources to foster innovation in green technology, The development stage of financial markets and the extent of executive stock ownership could affect how deeply digital technology is applied and the decision-making in green innovation. The study uncovers variances in eco-friendly innovation among companies amid digital evolution by examining these aspects of diversity, offering clearer policy advice for decision-makers.

This document's key achievements include: Utilizing extensive microdata from manufacturing companies for the first time to develop metrics for assessing digital transformation. Utilizing Python methods for identification and extraction the research quantifies "digital transformation" by analyzing the occurrence of pertinent terms, based on keywords from yearly summaries. Investigating how digital transformation affects innovation in green technology bridges the empirical void in current studies and provides crucial understanding for the comprehensive green transformation and enhancement of China's manufacturing industry.(2) This research enhances comprehension of how digital transformation indirectly affects green innovation by incorporating financial and economic growth as intermediary factors, thereby enriching associated theoretical studies.(3) This study, utilizing multidimensional heterogeneity analysis, uncovers the diverse impacts of digital transformation on green technology innovation across various business environments, offering actionable policy suggestions for progress in dig transformation in Italy and eco-friendly advancements within the manufacturing industry.

2. Literature Review

2.1. The Relationship Between Digital Transformation and Technological Innovation in Enterprises

The adoption of digital transformation as a crucial tactic for businesses to adapt to worldwide

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rivalry and technological shifts is transforming their models of innovation and organizational frameworks. Through the incorporation of advanced technologies like the Int In the realms of IoT, big data, and AI, firms have transitioned from conventional production methods to smart manufacturing and automated systems [9]. This change markedly enhances operational effectiveness and also leads to significant advancements in the scope and profundity of technological innovation [10]. By breaking information silos and enhancing both internal and external information flow, digital technologies enable enterprises to quickly and accurately capture market demands and technological change trends, thus gaining an advantage in product development and process innovation.

The role of digital transformation in driving innovation is especially noticeable in the manufacturing sector. Smart manufacturing systems, through real-time data monitoring and analysis, optimize product design and production processes, accelerating technological iteration while effectively reducing resource waste and environmental burdens [11]. This new innovation ecosystem not only shortens R&D cycles but also provides unprecedented flexibility and adaptability for the technological upgrading of enterprises.

Yet, even though the beneficial influence of digital transformation on tech innovation is broadly acknowledged, its precise impact on eco-friendly tech innovation still requires thorough investigation. Current scholarly works primarily concentrate on the impact of digitalization on conventional technological advancements is evident, yet the discourse on its role in fostering environmental change remains disjointed, devoid of structured theoretical models and empirical backing. This implies that additional investigation into digital transformation's role in propelling eco-friendly technological advancements holds considerable scholarly merit and practical importance for businesses aiming for sustainability. objectives for the growth of able.

2.2. The Relationship Between Digital Transformation and Green Technological Innovation

Green technological innovation is an important strategy for enterprises to achieve sustainable development in the face of environmental pressures and market competition. It not only meets increasingly stringent environmental requirements by reducing energy consumption and pollution emissions, but also creates competitive advantages and economic benefits for enterprises. Within this framework, digital transformation is regarded as a principal catalyst for eco-friendly technological advancements [12]. The profound integration of digital technologies, especially IoT and big data analytics, empowers firms to accurately oversee and enhance resource utilization and environmental effects throughout production phases, facilitating immediate control. and astute administration, thereby enhancing the efficiency of resources and reducing ecological strain.

Two primary factors mirror the influence of digital transformation on eco-friendly technological advancements: On the one hand, through intelligent systems and data analysis, it helps enterprises achieve breakthroughs in energy conservation, emission reduction, and resource recycling [13]. On the other hand, by enhancing market forecasting capabilities and consumer demand analysis, it supports the commercialization and promotion of green technological innovations. This skill not only hastens the creation of eco-friendly products but also improves the adaptability and focus of businesses in fulfilling market needs, injecting fresh energy into green innovation.

Nonetheless, present studies mainly concentrate on developing theoretical models and case analyses regarding the role of digital transformation in fostering eco-friendly technological advancements, while there's a dearth of structured empirical research on its distinct mechanisms and diversity. harmful effects across varied business environments. This constraint impedes the comprehensive advancement of theoretical frameworks and curtails their real-world implementation. Consequently, the subsequent theory can be suggested:

Hypothesis 1: Digital transformation significantly enhances the level of green technological innovation in enterprises.

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2.3. Financial Development, Economic Development, and Green Technological Innovation

Financial development and economic development are important external factors affecting green technological innovation in enterprises. Developed financial markets provide enterprises with diversified financing channels, such as green bonds and green funds, which specifically support environmental protection and green innovation [14]. Such financial instruments are essential for financing the eco-friendly tech innovation endeavors of companies. Moreover, regions with higher levels of economic development typically have more advanced infrastructure and policy environments, creating a favorable innovation ecosystem for enterprises, thus fostering the creation and utilization of eco-friendly technologies. Research indicates that the levels of financial and economic growth play a crucial role in both the accessibility of innovation resources for businesses and their overall influence. regarding their strategic decisions and the vigor of their innovation in eco-friendly technology.

Within the realm of digital evolution, the significance of financial and economic growth stages grows more evident. Implementing digital technologies broadly typically demands significant financial commitment., especially when enterprises are engaged in smart manufacturing and big data analysis, which greatly increases their dependence on capital. Advanced financial markets have the potential to enhance the efficiency of financing pathways and cut down on costs, thereby encouraging businesses to invest more in eco-friendly technological advancements amidst the digital transformation phase [15]. Furthermore, areas experiencing advanced economic growth not only cater to the market's need for eco-friendly products but also encourage the spread and utilization of green tech innovations via policy backing and market strategies.

While current research has delved into how financial and economic growth influence corporate innovation efforts, the significance of financial and economic growth stages as intermediaries in the link between digital currency The process of transformation and eco-friendly technological advancements remains unconfirmed. Consequently, this research presents levels of financial and economic growth as intermediary factors to investigate their indirect impact on green tech innovation.

Consequently, the ensuing hypotheses are suggested.:

Hypothesis 2: Digital transformation in enterprises indirectly enhances the level of green technological innovation through improving financial development levels.

Hypothesis 3: Digital transformation in enterprises indirectly enhances the level of green technological innovation through improving economic development levels.

Adhering to this rational structure, the paper develops a framework for digital transformation mechanisms, grounded in the viewpoints of financial and economic growth stages, as depicted in Figure 1.

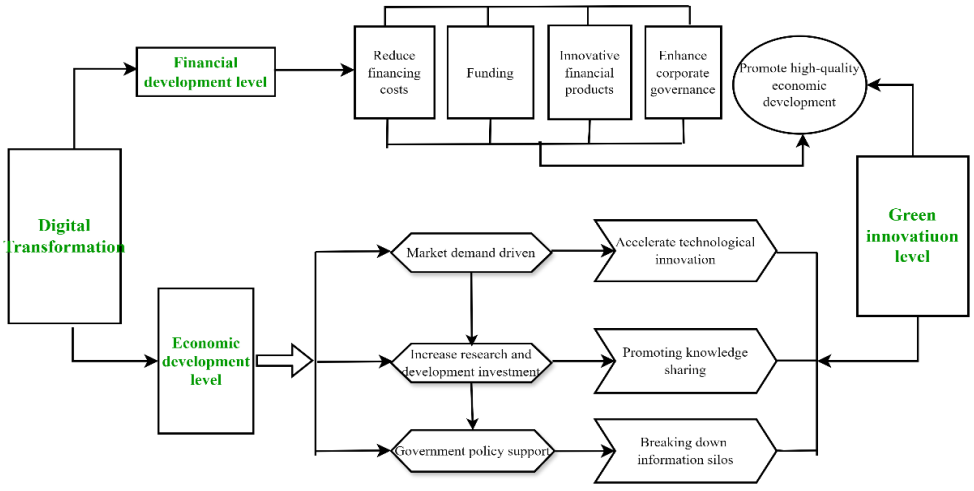

Figure 1.
Mechanism diagram.

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2.4. The Position of this Paper

Theoretical investigations have delved into how digital transformation correlates with eco-friendly technological advancements., significant gaps remain in existing research. First, most studies rely on qualitative analysis and case studies, lacking empirical analysis based on large-scale enterprise data, which limits the generalizability and applicability of their findings. Second, there is limited attention to the heterogeneity effects of different corporate contexts in the literature, particularly regarding ownership structure, company size, and financial market environment [16]. The differences in how firms experience digital transformation may significantly impact their green technological innovation capacity, yet this aspect remains insufficiently investigated. Furthermore, the intermediary function of financial and economic growth levels as external elements in the link between digital evolution and eco-friendly technological advancements remains unaddressed. n methodically examined. Existing research often treats these factors as independent variables, overlooking their potential mediating role in the complex innovation mechanisms [17].

This study shares core commonalities with previous research but also presents notable differences. Initially, it advances the dialogue on the link between digital evolution and tech innovation, broadening this concept to encompass green tech innovation, emphasizing the role of digital transformation in fostering innovation. ion in the realm of ecological sustainability. Secondly, this paper introduces financial and economic development levels as mediating variables, exploring their indirect impact in the process of digital transformation promoting green technological innovation, thus expanding the existing theoretical framework and providing new empirical insights for policy formulation. Unlike previous studies that treat these factors as independent variables, this paper emphasizes their mediating effects. Furthermore, through heterogeneity analysis, this research delves into the varied achievements of different business types regarding eco-friendly technological advancements amid digital evolution, focusing especially on the impact of ownership frameworks, the financial market conditions, and execution. Holding shares in e. The study offers specific policy advice to foster eco-friendly technological advancements in companies from varied backgrounds.

3. Data and Methodology

3.1. Sample Selection and Data Sources

The research focuses on Chinese A-share manufacturers featured on the Shanghai and Shenzhen stock exchanges between 2010 and 2022 to empirically assess how digital transformation influences green technological innovation. n. Businesses marked as S, ST, and *ST are omitted from the preliminary sample. Firms registered post-2010 are omitted to guarantee that the chosen sample encompasses those listed from 2010 to 2022. Companies exhibiting discontinuities or notable gaps in data during this timeframe are omitted, culminating in a total of 6,604 observations per firm year. Winsorization is utilized on the initial data to reduce the impact of anomalies at the for every variable, there are 1% of the highest and lowest percentiles. All micro-level data is sourced from the CSMAR database, and macro-level data is obtained from the WIND database.

3.2. Variable Definitions

3.2.1. Dependent Variable

The assessment of Green Technological Innovation (Gil) encompasses two viewpoints: the input angle, utilizing R&D spending as a measure of green tech innovation investment, and the output angle, assessing innovation through patent filings, encompassing patents for green inventions, green utility models, and green design patents. Evaluating Green Technological Innovation (Gil) involves two perspectives: the input angle, which uses R&D expenditure to gauge investment in green tech innovation, and the output angle, focusing on innovation via patent applications. ng patents pertaining to eco-friendly innovations, sustainable utility models, and green design patents.

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3.2.2. Core Independent Variable

This research focuses on the firm's digital transformation (DT) as the independent variable. In the era of the digital economy, companies are frequently compelled to persistently innovate and evolve for their growth, resulting in extensive alterations in their operations. operations related to being. Annual reports, mirroring a company's operational achievements in the previous year, are adept at documenting the behavioral shifts linked to its digital evolution. Consequently, this research retrieves the yearly summaries of every manufacturing company listed on the Shanghai and Shenzhen stock exchanges from the Cninfo website (www.cninfo.com.cn), followed by the extraction and compilation of textual data from these records. Utilizing a digital transformation's keyword frequency spectrum (refer to Table 1 for a detailed frequency distribution). The gathered data is correlated with keywords related to digital transformation, and the frequency of each keyword is measured and paired with the firm data to construct a basic digital transformation indicator system. Given the right-skewed distribution of the indicators, logarithmic transformation is applied to the final indicators.

Table 1.
Key text words for DIT.

Dimension	Keywords
Artificial intelligence technology	AI, VR, 3D, face recognition, biometrics, voice recognition, identity verification, intellectualization, networking, e-commerce, online to offline, offline to online, online and offline, intelligent energy, intelligent transportation, intelligent networking, intelligent agriculture, intelligent terminals, intelligent logistics, intelligent factories, intelligent environmental protection, intelligent production, intelligent equipment, intelligent systems, intelligent control, mobile Internet, Internet mode, Internet ecology, Internet platform.
Big data technology	large-scale data, administration of data, platform for data, synchronization of data, digital interface, safeguarding data, digital backdrop, digital production, automated downloading, automated analysis, system transition, automated detection, monitoring, and automated production. Manufacturing, data organization, data hub, data system, data network, data exchange, data administration, data amalgamation.
Cloud computing technology	Cloud computing, IT solutions, services, documents, conferences, platforms, industrial clouds, and synchronization of clouds.
Blockchain technology	Various payment methods including mobile, third-party, fingerprint, Apple Pay, Air Play, apple pencil, Apple Watch, digital currency, open banking, keys, CNC, digital space, hybrid reality, unmanned shelves, and integration.

3.2.3. Control Variables

Drawing from current studies, this research identifies various control variables linked to a company's financial traits and ownership framework, encompassing aspects like size (Size), leverage ratio (LEV), duality (Dual), capital intensity (Tang), and company expansion (Gro with), along with the concentration of ownership (Coo). The specific definitions of these variables are provided in Table 2.

3.2.4. Mediating Variables

This study selects economic development level (Led) and financial development level (Lfd) as mediating variables. The specific definitions of these variables are provided in Table 2.

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Table 2.
Variable definition table.

Variable type	Variable symbols	Variable Name	Measurement method
Dependent variable	GIL	Green innovation level	Number of applications for green patents
Core explanatory variable	DT	Digital Transformation	Annual reports
Control variables	Lev	Asset liability ratio	Liabilities/Total Assets
	Size	Enterprise scale	The logarithmic value of total assets
	Tang	Capital intensity	Net value of fixed assets of the enterprise/average number of employees of the enterprise
	Age	Enterprise age	Current year - year of business opening+1 logarithm
	Growth	Enterprise growth potential	Market value/asset replacement cost
	Coo	Equity concentration	Total shareholding ratio of the top ten shareholders
	Dual	Integration of two positions	1 for a dual role enterprise, and 0 for the rest
Mediating variables	Led	Economic development level	Regional GDP logarithm
	Lfd	Financial development level	Total loans from regional financial institutions/GDP

3.3. Model Specification

The creation of the National Big Data Comprehensive Pilot Zone presents an external policy surprise for companies, which may have differentiated effects based on the environmental attributes of the firms. This variation allows for the fulfillment of the basic assumptions of the Difference-in-Differences (DID) method. Since the Big Data Comprehensive Pilot Zone was established in two phases, from 2015 to 2016, different firms were affected by the policy at different points in time. Therefore, this study constructs a multi-period Difference-in-Differences model to analyze the impact of the establishment of the National Big Data Comprehensive Pilot Zone on the digital transformation of manufacturing firms. The specific model is as follows:

$$GIL_{it} = \beta_0 + \beta_1 * DT_{it} + \sum \beta_i * Control_{it} + \sum \gamma + \sum \mu + \varepsilon_{it} \quad (1)$$

Where, DIT represents the degree of digital transformation of enterprises, and $Treat * Post$ is the product of spatial dummy variables and time dummy variables. β is the policy effect studied in this paper; X represents the control variable. This paper also adds industry fixed effect γ and year fixed effect μ; i represents enterprise, t represents year, and ε represents random disturbance term.

In the above test model: i represents listed companies, t represents year; the explained variable GIL represents the measurement index of green technology innovation of enterprises; the explanatory variable DT represents the degree of digital transformation of enterprises. The larger the DT value, the higher the degree of digitalization of enterprises; Control is a series of control variables. In addition, this paper also controls the year fixed effect μ and individual fixed effect γ.

4. Empirical Analysis

4.1. Descriptive Statistics

Table 3 illustrates that the average worth of corporate green technological innovation (Gil) stands at 4.43, peaking at 142 and exhibiting a standard deviation of 18.074, signifying significant variability. This indicates notable disparities in the level of eco-friendly tech advancements within the sampled companies. The digital transformation indicator (DT) varies between 1.2 and 4.4, exhibiting a standard deviation of 1.214, indicative of the degree of fluctuation in the digital transformation level. With an average DT value of 1.148, it implies a need for further enhancement in the digital transformation

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processes of the sampled companies. Additional control variables align with the results of current studies and will not be elaborated upon.

Table 3.
Descriptive analysis results.

Variable	Obs.	Mean	Std.	Min	Max
Gil	6604	4.43	18.074	0	142
DT	6604	1.148	1.214	0	4.407
lev	6604	0.433	0.189	0.056	0.828
size	6604	22.459	1.273	20.195	26.406
tang	6604	12.66	0.865	10.574	14.918
age	6604	3.258	0.189	2.773	3.638
tbQ	6604	2.11	1.273	0.889	8.17
coo	6604	0.54	0.151	0.222	0.918
dual	6604	0.24	0.427	0	1
led	6604	17.903	1.081	15.464	19.912
lfd	6604	1.453	0.682	0.399	3.48

4.2. Benchmark Regression Analysis

Table 4's Column displays the regression outcomes for the influence of digital transformation on eco-friendly technological advancements in manufacturing companies, illustrating the impact of digital transformation on such innovation without Incorporating control variables or constant effects. The outcome holds statistical significance at the 1% threshold. Column displays the regression analysis incorporating fixed effects for individuals and years, yet omitting control variables. The column incorporates control variables, disregarding any fixed effects. The column takes into account control variables and fixed effects at the same time. The regression coefficients for the effect of digital transformation on green technological innovation in manufacturing firms under different scenarios are 2.753, 1.960, 0.665, and 1.541, all of which are significant at the 1% level. The findings confirm that digital transformation markedly boosts eco-friendly technological advancements, showing a beneficial and anticipatory impact.

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Table 4.
Benchmark regression analysis results.

	(1)	(2)	(3)	(4)
	Gil	**Gil**	**Gil**	**Gil**
DT	2.752***	1.960***	0.665***	1.541***
	(15.29)	(4.90)	(3.71)	(9.62)
lev			-3.196**	0.131
			(-2.55)	(0.10)
size			6.720***	1.109***
			(32.00)	(4.18)
tang			-1.447***	0.623**
			(-5.66)	(2.21)
age			-5.030***	-760.948***
			(-4.59)	(-7.03)
tbQ			0.433**	0.278**
			(2.50)	(2.09)
coo			3.360**	2.854*
			(2.42)	(1.95)
dual			3.077***	-0.668*
			(6.57)	(-1.74)
I Fe	No	Yes	No	Yes
Year FE	No	Yes	No	Yes
_cons	1.271***	2.180***	-114.631***	2447.212***
	(4.22)	(4.75)	(-20.66)	(6.93)
N	6604	6604	6604	6604
R^2	0.334	0.345	0.407	0.481

4.3. Endogeneity Test

This research utilizes the Heckman two-stage approach for the endogeneity test to mitigate the effects of sample selection bias. Initially, the primary phase involves determining if a company possesses an eco-friendly patent application for the specified year as the dependent. nt variable. The construction of a Probit model aims to calculate the likelihood of a company submitting an eco-friendly patent application, followed by deriving the inverse Mills ratio (Imr). Subsequently, during the second phase, the inverse Mills ratio (Imr) is incorporated as a controlling factor into the primary regression model for further examination. The results show that the green innovation level is significantly positively correlated with the inverse Mills ratio (Imr), indicating that the original baseline regression suffers from sample selection bias. However, as seen from the results in Column (2) of Table 5, even after considering the sample selection bias, the green innovation level (GIL) and digital transformation (DT) remain significantly positively correlated at the 1% level.

Table 5.
Endogenous test results.

	(1)	(2)
	Phase 1	Phase 2
DT	0.152***	19.451***
	(4.25)	(4.69)
imr		168.190***
		(4.62)
_cons	-5.323***	925.610***
	(-4.35)	(2.63)
control	Yes	Yes
I FE	Yes	Yes
Year FE	Yes	Yes
N	6604	6604
R^2	0.624	0.794

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4.4. Robustness Check

4.4.1. Replacing the Dependent Variable

To further verify the robustness of the regression results, this study replaces the dependent variable, green innovation level, using the aggregate count of green patents issued as an alternative to the overall number of green patent applications. The data in Table 6's Column reveal that substituting the dependent variable (green patent applications) with Despite the total green patents issued, digital transformation continues to positively influence the company's level of green innovation. This implies that digital transformation fosters corporate eco-friendly innovation, as evidenced by the overall count of green patent applications or patents issued.

4.4.2. Changing the Sample Time Period

This study's chosen sampling timeframe spans from 2010 to 2022, known for its considerable length. To guarantee that the influence of digital change on levels of green innovation remains unaffected by the duration of the sample period, a new sample period from 2011 to 2021 is chosen, and the benchmark model is re-tested. Table 6's Column reveals that the core variable's coefficient continues to be notably positive. This confirms that the time window selected in this study is appropriate for accurately estimating the impact of digital transformation on corporate green innovation levels.

4.4.3. Adjusting the Sample Size

In contrast to typical prefecture-level cities, Beijing, Tianjin, Chongqing are the four municipalities directly governed by the central authority. and Shanghai—often have advantages in resource acquisition, with larger economic scales and better human resources than ordinary prefecture-level cities. The unadjusted sample size may overestimate the impact of digital transformation due to the presence of companies from these special cities. Therefore, this study further removes the samples from Beijing, Tianjin, Chongqing, and Shanghai, and re-estimates using Model (1). The results, shown in Column (3) of Table 6, indicate that after excluding these four municipalities, the level of corporate green innovation still increases due to policy implementation, further corroborating the beneficial effects of digital change on levels of green technological advancement.

4.4.4. Lagging the Dependent Variable by One Period

Considering that the output cycle of green innovation is generally long, in this research, regression analysis is performed by delaying the dependent variables—level of green innovation, quality of green innovation, and quantity of green innovation—by one and two intervals. Results of the regression analysis are displayed in Table 6. As observed in Column of T able 6, despite considering the delayed impact of eco-friendly innovation, digital transformation continues to markedly enhance corporate eco-friendly innovation at a 1% rate.

Table 6.
Results of robustness test analysis.

	(1)	(2)	(3)	(4)
	Replace the explained variable	**Change sample time interval**	**Adjusting sample size**	**Gil_1**
DT	4.243***	1.723***	1.047***	1.435***
	(4.12)	(8.93)	(7.47)	(8.67)
_cons	6.819***	-42.605***	1981.106***	-41.202***
	(5.69)	(-5.95)	(7.05)	(-6.83)
Control	YES	YES	YES	YES
I FE	YES	YES	YSE	YSE
Year FE	YES	YES	YSE	YSE
N	6604	5588	5476	6096
R^2	0.401	0.371	0.378	0.448

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4.5. Heterogeneity Analysis

4.5.1. Heterogeneity Test Based on Financial Market Environment

In order to fully leverage digital transformation and promote the improvement of green innovation levels, companies not only require external drivers, such as government support, but also need internal adjustments to continuously optimize the allocation of financial resources at the market level. However, due to differences in the market processes and the availability of human and economic resources across regions, the financial market environment varies from place to place. The question arises: does the disparity in financial market environments lead to heterogeneous effects of digital transformation on corporate green technological innovation?

The columns in Table 7 illustrate how digital transformation affects levels of green technological innovation in various financial market scenarios. One can notice that within advanced financial market settings, digital tra the development of ns markedly influences levels of green tech innovation, whereas in less developed areas, this impact is negligible. The underlying reason is that in developed financial market environments, companies have better access to funds, providing a solid financial foundation for research and development. Moreover, compared to underdeveloped financial markets, advanced financial markets are characterized by stronger mechanisms for market oversight and a more conducive financial climate. This motivates firms to participate in beneficial competitive practices, jointly seek enduring advantages, and create synergies, which is beneficial for enhancing the standard of eco-friendly technological advancements.

Table 7.
Based on the heterogeneity test results of the financial market environment.

	(1) Developed financial markets	**(2) Underdeveloped financial markets**
DT	2.271***	1.196
	(4.46)	(1.34)
_cons	2.405***	0.619
	(4.00)	(0.79)
Control	YES	YES
I FE	YES	YES
Year FE	YES	YES
N	5915	689
R^2	0.407	0.360

4.5.2. Heterogeneity Test Based on Ownership Structure

As shown in previous empirical analysis, digital transformation has a significant positive impact on corporate green technological innovation. However, considering the differences in ownership structure between enterprises, their business models and management practices may vary, which could lead to heterogeneous effects of digital transformation on green technological innovation. Therefore, Companies are categorized into state-owned and non-state-owned based on their ownership composition, and the varied impacts of digital transformation on eco-friendly technological advancements are examined for these categories. The data in Table 8's columns reveal that digital transformation impacts the levels of green technological innovation in both state-owned and non-state-owned companies, as indicated by the regression coefficient for St. Enterprises owned by the state show a notably positive trend at the 1% threshold. This suggests that digital transformation has a greater impact on the degree of eco-friendly technological advancements in state-owned businesses than in non-state-owned corporations. The likely reason is that state-owned enterprises, backed by the credibility of the government, have easier access to financing and investment. With sufficient funds, state-owned enterprises are more capable of undergoing organizational reforms and accelerating the process of enhancing green innovation. In contrast, non-state-owned enterprises, operating in a more competitive market environment, face fewer resources and, therefore, experience a less significant improvement in their green innovation levels.

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4.5.3. Heterogeneity Test Based on Executive Stock Ownership

To examine whether digital transformation has different effects on the level of green technological innovation for companies with varying levels of executive stock ownership, we divide the sample into two groups: companies with an executive stock ownership ratio above the average and companies with an executive stock ownership ratio below the average. The regression results are presented in columns (3) and (4) of Table 8. It can be observed that digital transformation has a greater impact on the green technological innovation level of companies with higher executive stock ownership ratios. The reason for this is that executive stock ownership, as an effective incentive mechanism, reduces agency costs and moral hazards, aligning the interests of managers with those of stakeholders. Therefore, in the context of digital transformation, companies with higher executive stock ownership ratios are under greater pressure to enhance their green technological innovation levels, driven both by the need for the survival of the enterprise and the personal reputation of the managers.

Table 8.
Based on the heterogeneity test results of property rights and executive shareholding ratios.

	(1) state owned	(2) non-state-owned	(3) low shareholding ratio of executives	(4) high shareholding ratio of executives
DT	4.144***	1.125***	0.991***	1.978***
	(5.63)	(7.93)	(5.99)	(5.60)
_cons	1.768	-13.504***	-27.365***	3.528***
	(0.63)	(-2.60)	(-4.20)	(4.45)
Control	YES	YES	YES	YES
I FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
N	1430	5174	3341	3263
R^2	0.265	0.391	0.348	0.435

5. Mechanism Test

5.1. Model Setting

Develop a model for mediation effects to examine how the digital evolution of businesses influences their advancement in green technology.l:

$$Inter = \omega + \omega_1 * DT_{it} + \sum \omega_2 * \text{Control}_{it} + \sum \gamma + \sum \mu + \varepsilon_{it} \quad (2)$$

$$GIL_{it} = \upsilon + \upsilon_1 * DT_{it} + \upsilon_2 * Inter + \sum \upsilon_3 * \text{Control}_{it} + \sum \gamma + \sum \mu + \varepsilon_{it} \quad (3)$$

Among them, $Inter$ is the intermediary variable, and the meaning of other variables remains unchanged. ϖ_1 reflects the impact of the enterprise's digital transformation on the intermediary variables, and υ_2 reflects the impact of the intermediary variables on the enterprise's green technology innovation level. Using stepwise regression, if both are significant, it indicates the existence of a mediating effect.

5.2. Mechanism Test

The regression outcomes for the influence of corporate digital transformation on the financial development landscape and the impact of financial development level on corporate green technological innovation, respect, are displayed in Columns and of Table 9. vigorously. Within this column, the influence of digital transformation on the level of financial development shows a notably positive effect at the 1% level, suggesting that the advent of digital transformation truly boosts financial progress. Within this column, the influence of financial growth on the advancement of corporate green technology continues to be substantial, indicating the degree of green technology. The evolution of finance plays a role in fostering innovation in technology. Therefore, financial development plays an

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intermediary role in the process through which digital transformation affects corporate green technological innovation. The prosperity of finance serves as a safety net for enterprises, helping them overcome the challenges of technological innovation and reducing the costs they incur.

Columns (3) and (4) in Table 9 provide the regression results for the impact of digital transformation on economic development level and the effect of economic development level on corporate green technological innovation, respectively. Both regression results are significantly positive at the 1% level, indicating that digital transformation improves the economic development level, and that an increase in economic development further boosts the level of corporate green technological innovation. Thus, economic development plays an intermediary role in the relationship between digital transformation and green technological innovation. As economic development improves, enterprises benefit from a better business environment, which provides more time and resources for innovation. Consequently, the better the economic development, the higher the level of corporate green technological innovation.

Table 9.
Mechanism verification analysis results.

Variables	Gil	Lfd	Gil	Gil	Led	Gil
	(1)	(2)	(3)	(4)	(5)	(6)
DT	1.541***	0.181***	2.714***	1.541***	0.270***	2.517***
	(9.62)	(27.73)	(14.27)	(9.62)	(25.85)	(13.34)
Lfd			1.009*			
			(1.95)			
Led						0.870***
						(4.11)
Control	Yes	Yes	Yes	Yes	Yes	Yes
I FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
N	6604	6604	6604	6604	6604	6604
R^2	0.481	0.309	0.542	0.481	0.395	0.490

6. Managerial Implications

Drawing from its research outcomes, this study suggests these policy suggestions.:

1.Enhancing Comprehensive Support for Corporate Digital Transformation. The government should intensify support for the digital transformation of manufacturing enterprises, particularly in terms of financial aid, tax incentives, and green innovation policies, to help firms quickly adapt to digital transformation trends. First, the government should expand fiscal subsidies for the application of digital technologies and tax reductions for green technology R&D, thereby reducing the cost burden on companies during the digital transformation process. Secondly, it's advisable for the government to create specialized funds for green innovation to aid businesses, especially those of small and medium scale (SMEs)., in enhancing their green technology R&D capabilities during the digital transformation process. This will help improve resource efficiency and environmental sustainability. Additionally, the government can set up innovative demonstration projects to provide benchmark cases for companies, encouraging them to learn from and follow these examples.

2.Formulating Differentiated Policies to Promote Green Technological Innovation in Different Types of Enterprises. The development of policies needs to be enhanced, incorporating varied support strategies tailored to the unique contexts of diverse business types. For state-owned enterprises, the government should continue to leverage their funding and policy support advantages by offering more green financing tools (e.g., green bonds, green funds) and fiscal subsidies to encourage greater investment in green technological innovation. Moreover, policy guidance for state-owned enterprises should emphasize the integration of green innovation with national sustainable development goals. For private enterprises, the government should focus on improving the financial market environment, particularly strengthening financing support for green innovation projects. By introducing innovative green financial products (such as green loans, green insurance) and risk compensation mechanisms, the

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government can help private enterprises access more funding sources and alleviate financing difficulties for green technological innovation.

3.Strengthening Regional Financial Support to Promote Regional Green Innovation. Given the differences in financial market environments, economic development levels, and resource allocation across regions in China, the government should strengthen support for financial markets in underdeveloped regions, particularly in terms of green finance and funding for digital transformation. The government can establish dedicated green development funds and local policy tools for promoting green finance in underdeveloped regions, providing more convenient green financing channels for local enterprises. Moreover, the government should encourage local governments and financial institutions to cooperate in promoting the innovation of green financial products, helping regional enterprises reduce capital costs and improve access to funding during their digital transformation and green technological innovation processes. Additionally, the government should promote collaborative innovation and knowledge-sharing within regions through regional green technology R&D platforms.

4.Strengthening Policy Guidance and Alignment with Corporate Green Transformation. The government should enhance policy guidance and synergy in the green industry to ensure effective alignment among policies, capital, and technology. For example, the government could use green industry policies to guide companies in promoting green production and innovation alongside their digital transformation. By introducing targeted policies, the government can encourage companies to adopt environmentally friendly technological innovations during their digital transformation and promote the deep integration of digital and green technologies. Additionally, the government should strengthen awareness-raising and training efforts for corporate green transformation, helping companies overcome technological bottlenecks and management challenges in the process of green technological innovation. This will accelerate the widespread application and promotion of green technologies.

7. Theoretical Contributions

1. Broadening the Study of the Connection Between Digital Evolution and Eco-friendly Technological Advancement. The research enhances our understanding of how digital transformation affects corporate innovation in green technology. E Current studies mainly concentrate on how digital transformation impacts corporate innovation at large, with scant attention to green technological advancements. By empirically analyzing the relationship between digital transformation and green technological innovation, this study fills this gap, demonstrating that digital transformation significantly promotes the realization of green technological innovation through optimizing resource allocation and improving production efficiency.

2. Unveiling the Mediating Influence of Levels in Financial and Economic Progress. This research pioneers the investigation into how financial and economic growth levels mediate the journey of digital transformation towards eco-friendly technology. innovation in physics. Previous studies have shown the beneficial impact of financial and economic growth on corporate innovation, yet their contribution to the link between digital transformation and eco-friendly technological advancements remains unclear. Through mediation analysis, this study enriches the existing theoretical framework by clarifying how financial and economic development levels, by providing resource support and market environments, indirectly promote corporate green technological innovation.

3. In-depth Analysis of Heterogeneous Effects. This study is the first to conduct a heterogeneity analysis in the existing literature, investigating how different corporate contexts (such as ownership structure, financial market environment, and executive stock ownership) moderate the relationship between digital transformation and green technological innovation. The study uncovers the varied achievements of different firms in the digital transformation journey and also offers more accurate advice to policymakers. This work tackles the research gap regarding the effects of the diversity within companies and expands the scope of studies focusing on digital evolution and eco-friendly innovation.

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8. Conclusion

Utilizing data from Chinese manufacturing companies listed on the A-share, this research methodically investigates how digital transformation affects corporate eco-friendly tech innovation, employing text analysis methods. Additionally, the research delves into the intermediary functions played by levels of financial growth and economic advancement in this procedure. Additionally, the study explores the diverse impacts of digital change on eco-friendly technological advancements throughout varied business environments, such as ownership structure, financial market environment, and executive stock ownership.

Findings show that the shift towards digitalization markedly fosters eco-friendly technological advancements through the efficient use of resources, reducing environmental pollution, and enhancing energy efficiency, thus providing strong support for firms' sustainable development. Financial and economic development levels indirectly facilitate green technological innovation by offering financial support and improving the market environment, further accelerating the impact of digital transformation.

Additionally, the study finds significant heterogeneity in the effects of digital transformation across different types of firms. In regions with well-developed financial markets, Companies stand a higher chance of securing monetary backing, thereby hastening the digital transformation and eco-friendly innovation. Government-run companies, reaping advantages from fiscal and policy backing, demonstrate a more pronounced ability to drive green technological innovation. Moreover, firms with higher executive stock ownership tend to engage more in green technological innovation during their digital transformation, as management's focus on long-term interests helps promote the implementation of green technologies. Based on these findings, the study provides relevant policy recommendations to offer guidance for policymakers.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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